PREFACE

THIS volume comprises the non-mathematical portions of a course of lectures, entitled " Electric Waves and their Application to Wireless Telegraphy," which for several years have been given by the author to classes at Harvard University. In giving the lectures and in preparing this volume, the design has been:— First, to present, in as elementary a form as possible, the course of reasoning and experimentation that has led to the conception of electric waves; second, to follow this with a discussion of the properties of electric waves and electric oscillations; third, to give a history of the application of electric waves to wireless telegraphy; and fourth, to elaborate the general principles and methods of electric-wave telegraphy in sufficient detail to be of possible use to elementary students of electricity and to amateur and professional electricians engaged in operating and constructing wireless telegraphic apparatus.

The author wishes to express his sincere thanks to Commander S. S. Robison of the United States Navy, to Mr. Elliott Woods of Washington, and to Chief Inspector D. M. Mahood of the New York Navy Yard for their kindness in supplying photographs for some of the illustrations. Also, the author is grateful to the Editors of the *Physical Review* for the loan of Plates I and II, and to Mr. Greenleaf Whittier Pickard for the privilege of consulting his manuscript account of experiments on the effects of daylight on transmission. Finally, the author takes great pleasure in expressing his gratitude to his friend Mr. George Francis Arnold, who has kindly read the proofs and made many valuable suggestions.

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INTRODUCTION

ALMOST every one has seen and heard the noisy, brilliant spark produced by the discharge of a Leyden jar. The experiment, shown in elementary courses in physics, is usually performed as follows: The inner and outer coatings of the Leyden jar are connected to the terminals of a static electric machine. The machine is set in rotation and the jar is charged. After the jar has been charged, the electric machine is disconnected, and one end of a metallic rod, held by an insulated handle (see Fig. 1), is

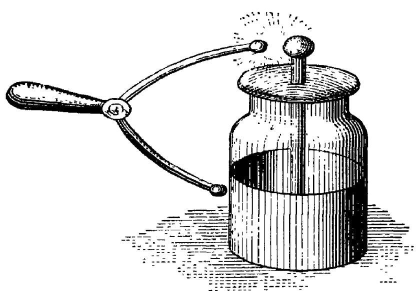

FIG. 1. Leyden jar and discharger.

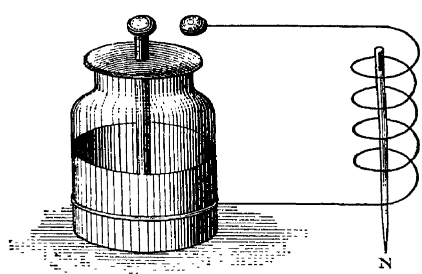

FIG. 2. Leyden jar with coil in discharge circuit.

touched against the outer coating of the jar, while the other end of the rod is made to approach a knob connected with the inner coating. Before the conductor to the inner coating is actually touched, a discharge occurs through the metallic rod, producing a vivid spark at the gap intervening between the knob and the discharge rod. As a variation of the experiment, in the place of the straight or slightly curved metallic rod used in the discharge apparatus of Fig. 1, a coil consisting of a few turns of heavy wire may

the Leyden jar always charged in the same direction by the electric machine used to charge the jar, the needle was sometimes found to be magnetized in one direction and sometimes in the opposite direction, indicating that the current that produced the magnetization of the needle was flowing in the coil in the one case from the outside of the jar towards the inner coating, while in the other case it was flowing from the inner coating to the outer coating. This effect could be explained by supposing that the current from the Leyden jar was oscillatory, having first one direction and then the other, and that the magnetization of the needle was reversed at each reversal of the current, the direction of the magnetization at the end of the experiment being fortuitously determined by the direction last taken by the current. Professor Henry's experiment, though not conclusive, gave strong evidence of the oscillatory character of the discharge; and the opinion that the discharge is oscillatory was repeatedly expressed and defended by Professor Henry in a number of papers and scientific addresses delivered between 1842 and 1850.

Sir William Thomson's Theoretical Proof of the Oscillatory Nature of the Discharge of the Leyden Jar. — In 1853 Sir William Thomson,[1] who was afterwards Lord Kelvin, proved by mathematical reasoning that under certain conditions the discharge of a Leyden jar occurs in an oscillatory manner. Under certain other conditions the discharge is non-oscillatory. In the case of the oscillatory discharge the electricity does not simply flow from one coating to the other until the jar is in a condition of electric neutrality, but rushes back and forth between the two coatings a great number of times, with a frequency depending on the dimensions of the jar and the dimensions and form of the coil through which the discharge occurs.

Feddersen's Revolving-Mirror Experiment. — In 1859 Doctor Feddersen of the University of Leipzig, by a very beautiful experiment, proved the correctness of the surmise of Henry and the mathematical predictions of Thomson. Feddersen's experiment consisted in photographing the spark produced by the discharge of the Leyden jar. A photograph similar to that obtained by Feddersen is shown in Fig. 3. A sketch of the apparatus used in taking the picture is shown in Fig. 4. Instead of employing an ordinary camera to take the picture, the light from the spark S, produced by the discharge of the jar, was allowed to fall upon

[1] Wm. Thomson: Philosophical Magazine [4], 5, p. 393, 1853.

Electric Waves. Maxwell's Theory. — In a letter to C. H. Cay, Esq., dated 5th of January, 1865, James Clerk Maxwell, then Professor of Physics in the University of Edinburgh, wrote:

"I have also a paper afloat with an electromagnetic theory of light, which till I am convinced to the contrary, I hold to be great guns."

This paper to which Maxwell referred contained a prediction, based on careful mathematical reasoning, that electric oscillations in a circuit produce electric waves in surrounding space, that these waves travel away with the velocity of light, and that light itself is simply a train of electric waves of extremely short wave length. This prediction of Maxwell, correlating the phenomena of light and electricity, is one of the most beautiful philosophic speculations in the history of science, and long remained without direct experimental confirmation; but now, thanks to the brilliant experiments of Heinrich Hertz, the existence of electric waves with properties intimately related to those of light waves is a well-established fact of experience capable of verification in even very elementary physical laboratories.

It is by means of these electric waves that the signals of wireless telegraphy and telephony are propagated through space.

In the succeeding chapters, we shall take up more in detail the course of reasoning that led to Thomson's and Maxwell's predictions, the course of experimenting that led to the proofs of the existence of their electric oscillations and electric waves, and the development of the very striking methods that have been employed in utilizing these electric oscillations and electric waves in the transmission of signals. The discussion will introduce some details apparently remote from commercial usefulness; but it should be borne in mind that it has been by means of persistent and laborious study of these details that the practical result has been attained.

trifying a body consists in adding to it a quantity of the positive fluid or taking from it a quantity of the negative fluid. The state of electrification of a body is hence determined by the *excess* in amount of one of the fluids over the other. In order to account for the fact that the appearance of electrification of one sign is always accompanied by the appearance of an equal amount of electrification of the opposite sign, the two fluids were supposed to be uncreatable and indestructible, so that the accumulation of positive electricity in one body is always accompanied by the loss of positive electricity in some other body. This is the principal property that the electrical fluids were supposed to have in common with ordinary material fluids; namely, *the property of conservatism in amount* according to which *the total amount of electricity in a given system can only be changed by the transfer of electricity through the boundary of the system.*

The electrical fluids, on the other hand, must possess properties that do not belong to the material fluids; for example, portions of the positive fluid must be supposed to repel each other, as do also portions of the negative fluid, while the two unlike fluids attract each other. Another property of the electrical fluids still more at variance with the known properties of material fluids is found in the fact that if we add equal quantities of the two electrical fluids to the same body, the condition of the body will be unchanged, so that according to this theory we must suppose that "the mixture of the two fluids in equal proportions is something so devoid of physical properties that its existence has never been detected." [1]

THE ONE-FLUID THEORY

Benjamin Franklin attempted to describe the phenomena of electricity in terms of a single fluid. According to his theory, one of the fluids, the positive, was retained and called *the electric fluid,* while the other, the negative fluid of the two-fluid theory, was replaced by ordinary matter. Quantities of the electric fluid were supposed to repel other quantities of the fluid according to the law of the inverse square of the distance and to attract matter according to the same law. Quantities of matter were supposed to repel each other and attract the electric fluid. According to Franklin's theory an excess of the electric fluid rendered the body positive, while a deficiency rendered it negative.

[1] J. J. Thomson, Electricity and Matter, Charles Scribner's Sons, 1904.

ciated with them an equal small quantity of electricity or an integral multiple thereof. That is, the charges we meet with are never fractional parts of the charge carried by the hydrogen atom; whence we may suppose that the latter charge is an elemental quantity of electricity. In discussing the evidence afforded by Faraday's experiments Helmholtz [1] says that "if we accept the hypothesis that the elementary substances are composed of atoms, we cannot avoid the conclusion that electricity, positive as well as negative, is divided into definite elementary portions which behave like atoms of electricity."

The study of the conduction of electricity through gases gives still stronger evidence of the atomic character of electricity. Gases under the action of certain agencies — Roentgen rays, ultra-violet light, radium, high electromotive forces, electric spark, etc. — become conductive and retain their conductivity long enough to permit a study of the mechanism by which the electricity is conducted. As in the case of the study of conduction in liquids, we are again "led to the conception of a natural unit or atom of electricity of which all charges are integral multiples, just as the mass of a quantity of hydrogen is an integral multiple of the mass of a hydrogen atom." [2]

By the study of conduction in gases definite information is obtained in regard to the magnitude of this charge. In a series of experiments performed chiefly at the Cavendish Laboratory of Cambridge University the quantity of electricity in one electrical atom is found to be 3.4×10^{-10} electrostatic c. g. s. units.[3] This quantity obtained from experiments on conduction in gases is the same as the quantity of electricity carried by one hydrogen atom in the electrolysis of liquids.

Mass of the Carriers of Electricity. — Also at the Cavendish Laboratory evidence as to the mass of the carriers of electricity has been obtained by an experimental determination of the ratio of e/m, in which e is the elemental charge and m is the mass of matter carrying the charge. The result obtained is that the mass of the carrier, *when the electricity is negative,* is about 1/1700 of the mass of the hydrogen atom. This mass is apparently the same

[1] J. J. Thomson, Electricity and Matter, p. 73, Charles Scribner's Sons, 1904.

[2] J. J. Thomson, Electricity and Matter, p. 83, Charles Scribner's Sons, 1904.

[3] The electrical units are defined in Appendix I.

was employed to produce a continuous flow of electricity in wires. This continuous flow of electricity in a wire or other conductor is an electric current, and was known to produce heating of the conductor through which it flows.

In 1820 a new impetus was given to a study of electricity and magnetism by the discovery by Hans Christian Oersted of Copenhagen that magnetism and electricity are interrelated. This discovery and some of its consequences is described in the succeeding paragraphs.

On the Production of a Magnetic Field by a Current of Electricity. — Oersted's discovery was nothing less than the important fact that when a pivoted magnetic needle is placed near a wire carrying a current of electricity, the magnetic needle tends to set itself at right angles to the wire which carries the electric current. If the current is reversed, the direction of the deflection of the magnetic needle is reversed. If the wire carrying the current is moved from a position below the needle to a position above the needle, the deflection of the needle is again reversed.

Oersted's discovery has been utilized in the construction of the galvanometer, which is a very delicate instrument for detecting and measuring small electric currents. The principle of the galvanometer is as follows: A magnetic needle pivoted as in the ordinary compass, so as to be free to move in a horizontal plane, will, if undisturbed, take up a position in the magnetic meridian of the earth; that is, the needle will point approximately north and south, (*M*, Fig. 5). Suppose, now, that a wire is passed alternately above and below the needle several times so as to form a coil (*C*, Fig. 5), with its windings in the plane of the magnetic meridian. Let a current be passed through the coil, so as to flow north above the needle and south below it; the north current above the needle and the south current below it both tend to deflect the north-seeking end of the magnetic needle to the west, so that the effect of the current on the needle is multiplied by the combined action of the several turns of the conductor around the needle. For a highly sensitive galvanometer, the magnetic needle instead of being pivoted is delicately suspended by a fine fiber of spun quartz.

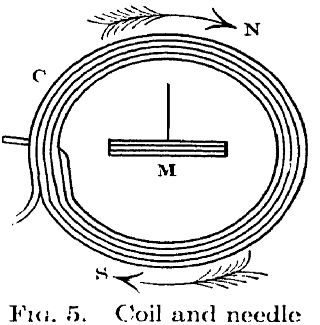

FIG. 5. Coil and needle of galvanometer.

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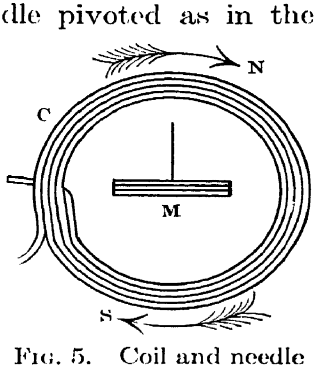

Fig. 5. Coil and needle of galvanometer.

solenoid the field of magnetic force is seen to be remarkably like that obtained with the bar magnet.

It may be observed that in the case of each of the coils the lines

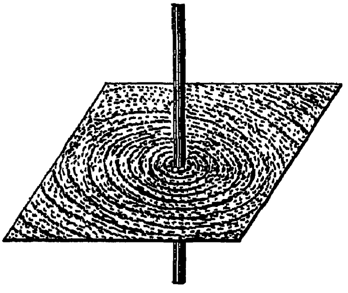

FIG. 7. Magnetic field about a straight conductor carrying an electric current.

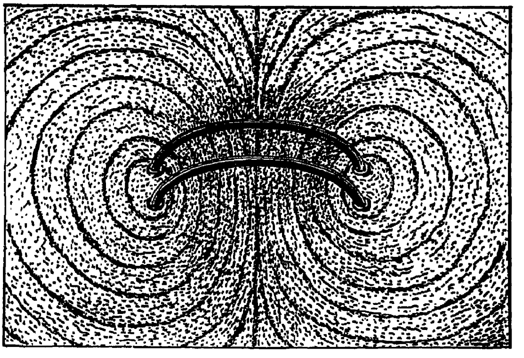

FIG. 8. Magnetic field linking with a coil of two turns carrying a current.

of magnetic force depicted by the filings interlink with the electric current.

This conception of a field of magnetic force about a conductor carrying an electric current is of fundamental importance in the study of electric waves, in which the action in the medium rather than the action in the wires is the chief factor to be reckoned with.

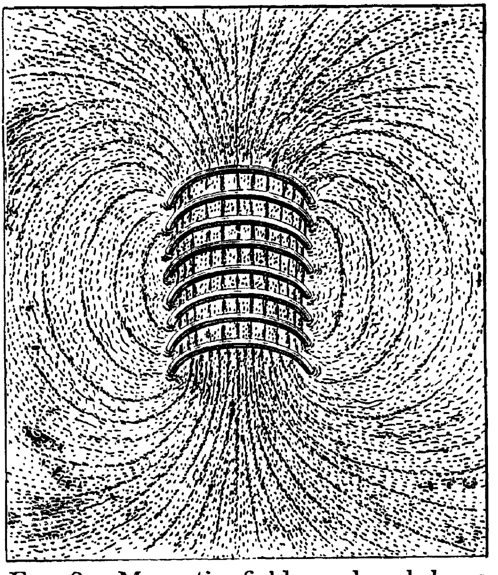

FIG. 9. Magnetic field produced by a solenoid.

So long as the electric current in the conductor remains steady, the magnetic field remains steady. With changes in the electric current, the magnetic field changes. This changing magnetic field about a conductor carrying an oscillatory current will later be shown to be one of the components of the electric waves produced at the sending station of a wireless telegraph system.

its own introduction, and in the same direction as that given by the introduction of the north pole.

Another way of obtaining a similar result is to employ two coils of wire placed near each other but not electrically connected, as

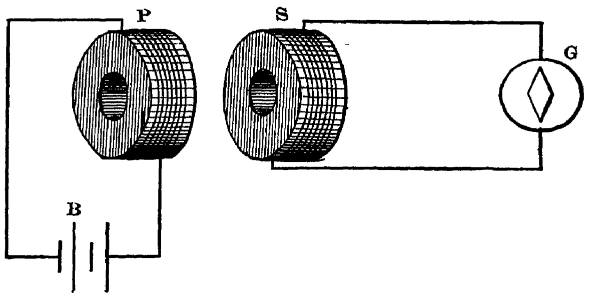

FIG. 11. Apparatus for showing electromagnetic induction.

shown in Fig. 11. One of these coils, S, which we will call the *secondary*, is connected with the galvanometer G, while the other, called the *primary*, P, may be connected with the terminals of a galvanic battery B. No current is shown in the galvanometer when a *constant* current is sent through the primary; but when the current in the primary is made, broken or reversed, transient currents are obtained in the galvanometer. That is to say, the current in the primary sets up a magnetic field linking with the secondary circuit. While the primary current is steady, this field is steady and no effect is obtained in the secondary. But variations of the current in the primary cause variations of the magnetic field and consequently currents in the secondary.

The variable currents in the secondary are said to be *induced* by the variable currents in the primary, and the phenomenon is referred to as *electromagnetic induction*. It is in part by action of this kind that currents at the receiving station of a wireless telegraph system are produced by the action of variable currents at the sending station. The extension of the effects of electromagnetic induction to the case of two circuits widely separated from each other we shall see to be the result of the use of extremely rapid electric oscillations at the sending station.

On Mutual Induction. — Let us examine a little more specifically the case of electromagnetic induction described in the galvanometer experiment cited above.

This experiment shows that when the current in the primary coil is increasing, the current induced in the secondary coil is in

tromotive force in the secondary is produced by a variable magnetic field from the primary interlinking with the secondary. Now, if instead of two coils we have one coil alone carrying a variable current, the variable current produces a variable magnetic field linking with the circuit itself, and in consequence a back electromotive force is produced in this coil tending to oppose the variation of the current in it. This action of the current on itself is called *self-induction.* The back electromotive force due to self-induction in the circuit is connected with the current in the circuit by the formula

$$E_1 = -L_1 \dot{I}_1, \tag{2}$$

in which L_1 is called the *coefficient of self-induction*, or, more briefly, the *self-inductance* of the circuit. $\dot{I}_1$ is an abbreviation for the time rate of change of the current. The subscripts 1 show that all the quantities refer to the same circuit.

Consistent with equation (2), *the self-inductance of a circuit may be defined as the back electromotive force of induction in the circuit when the current in the circuit is changing at the rate of one unit current per second.*

The numerical value of the self-inductance depends on the geometrical form of the circuit. In Appendix II formulas are given for calculating the self-inductance of some simple forms of circuit.

This discussion of self-inductance is here introduced in quantitative terms, because this quantity is of fundamental importance in the study of oscillatory currents. I am aware that the semi-mathematical form in which the idea is presented may fail to give a clear conception of the phenomenon, so I propose to attempt in the next chapter to describe self-induction by the aid of certain familiar analogies.

The correctness of this belief is evidenced by the fact that with a fixed current flowing in a wire the self-induction may be greatly increased by bending the wire into the form of a coil. Now making the wire into a coil does not change the amount of electricity flowing in the wire, but it does change the strength of the magnetic field about the wire. The inertia of the current, therefore, has its existence not primarily in the conductor but in the medium surrounding the conductor.

The Contrast of Self-Induction with Resistance and its Resemblance to Inertia. — The self-induction of a circuit acts upon the current in a manner entirely different from the manner in which resistance acts. The resistance of a circuit always opposed the flow of the current, and when a current is sent through a conductor, some of the energy of the current is used up in overcoming the resistance of the conductor; or, more properly speaking, some of the electric energy is converted into heat. This is true whether the current is increasing or diminishing or is steady; and the heat developed is not again completely available for producing electric current, so that a continuous supply of energy is needed at the source of the electric current to keep up the current against the resistance of the circuit.

Self-induction, on the other hand, does not change the electrical energy into heat. When the current is steady, self-induction has no effect. If, however, the current is increasing, some of the energy supplied to the system is employed in establishing the magnetic field. If now the current is allowed to decrease by an equal amount, the energy stored up in the magnetic field is restored to the conductor and helps to maintain the current. Thus, during a cyclic [1] change of the current as much energy may be obtained from the magnetic field as was given to it.

Hence, if we have an oscillatory current in a circuit, none of the energy of the current is consumed by the action of the self-induction, and the supply of energy at the source is wasted only in overcoming the resistance of the circuit.[2]

It is apparent that in respect to the consumption of energy self-induction resembles inertia in matter. Energy is required in order

[1] A cyclic change is a change from any value A to any other value B, and from B back to A again.

[2] Later we shall see that for some forms of circuit this statement is not strictly true, because some of the energy may be radiated as electric waves. Also in the case of some media, as *iron*, in the field of magnetic force, some of the energy is converted into heat by *hysteresis*.

CHAPTER V

ON ELECTROSTATIC CAPACITY

THE last two chapters have been devoted to a discussion of electric currents and the magnetic field accompanying such currents. In order to arrive at a conception of the nature of electric waves it is necessary also to give some attention to the action of electric charges at rest. This is the subject of *electrostatics*. Here again we must look to Faraday for the fundamental discoveries. In the beginning paragraph of his most important research on this subject Faraday says:[1]

"To those philosophers who pursue the inquiry zealously yet cautiously, combining experiment with analogy, suspicious of their preconceived notions, paying more respect to fact than to theory, not too hasty to generalize, and above all things, willing at every step to cross-examine their own opinions, both by reasoning and by experiment, no branch of knowledge can afford so fine and ready a field for discovery as this."

Influence of Intervening Medium on Electric Attraction. — The result obtained by Faraday in the research referred to is that the electrostatic repulsion or attraction between two charged bodies is influenced by the medium intervening between the charged bodies. If, for example, we have two flat metallic plates placed parallel to each other, and we charge one of the plates positively and the other negatively, the electrostatic attraction between the two charges on the plates will be less when the plates are separated by glass than when they are separated by air, provided the plates are charged with the same quantity of electricity in the two cases. The attraction between the charges on the plates with glass intervening will be about one-sixth as much as that with the same thickness of air intervening; so that in order to get the same force between the charges on the plates in the two cases we must put upon the plates with glass between them six times as much electricity as is required with air between.

[1] Faraday: Experimental Researches in Electricity and Magnetism, Vol. I, Eleventh Series, Nov., 1837.

Dielectric Constant. — Returning, now, to the function of the dielectric in determining the capacity of a condenser, the term *dielectric constant* of a substance is used to designate the capacity of a condenser with the substance as dielectric relative to the capacity of the same condenser with empty space as dielectric. The dielectric constant of air and all the gases at ordinary pressure is approximately unity; this means that the capacity of a condenser with a gas as dielectric is not much changed when the gas is pumped away. In the example cited above the dielectric constant of a particular glass is given as six; that is, the quantity of electricity that a condenser will contain under a given electromotive force with this glass as dielectric is six times the quantity the condenser will contain under the same electromotive force when air is substituted for the glass. A table of dielectric constants, together with some numerical formulas for calculating the capacity of some simple forms of condenser and rules for combinations of condensers in series and parallel, is given in Appendix II.

General Facts about Energy and Electromotive Force of Charged Condenser. — In order to send a charge of electricity into a condenser, energy is required, but the energy is not converted into heat, as it is in the case of a current of electricity flowing through a resistance; for the energy of the charge may be recovered as electric energy when the condenser is allowed to discharge. In a cyclic process in which a condenser is charged and discharged again, there is no loss of availability of energy in the processes that occur in the condenser. And when a condenser charges and discharges several times in an oscillatory manner, it is necessary to supply energy from without only in so far as the electric energy is radiated or is converted into heat in flowing through some resistance in the circuit.[1]

It has undoubtedly been observed by the reader that in respect to the reception of energy from the circuit and the return of the same amount of energy to the circuit again the medium of the condenser behaves somewhat like the medium of the magnetic field. There is, however, one marked difference. In the case of the magnetic field, the opposing *electromotive force* called into play by self-induction *is proportional to the rate at which the current is changing;* while, in the case of the condenser, the *electromotive force* V opposing the flow of electricity into the condenser *is proportional*

[1] This statement is not always strictly true, because in some forms of condenser a small part of the energy is consumed by *hysteresis* in the dielectric.

denser. After this condition is reached, no further current flows. This process of charging the condenser is described as gradual because time is required for the final condition to be established, but this time is usually very short.

Work Done in Charging Condenser. — During this process of charging the condenser, the average e.m.f. of the condenser was $\frac{1}{2} E$; the work[1] done, which is the charge introduced multiplied by the e.m.f. of the condenser, is $Q \times \frac{1}{2} E$; or, substituting for Q its value EC, the work W done in charging the condenser is

$$W = \frac{1}{2} E^2 C.$$

[1] See definitions of electrical work, in Appendix I.

released. The column of water will vibrate back and forth in tube so that its level in the left-hand arm of the tube comes successively above and below the position *a*. During each excursion the amplitude of the motion is diminished till the water finally comes to rest in its initial position.

Both of these forms of mechanical vibratory motion are easily realized in practice, and both bear a marked resemblance to the flow of electricity in the discharge of a condenser through an inductance and resistance.

In order now to understand how a condenser discharge may be oscillatory in character, suppose a Leyden jar, or other form of electrical condenser, of capacity C to be initially charged, say from an electric machine, with a quantity of electricity $+Q_0$ on one plate and $-Q_0$ on the other. And suppose that the condenser has in series with it a self-inductance L, and a spark gap S. (Fig. 14.) At first let the spark gap be too wide for the spark to pass. Positive electricity will be distributed over the one coating and one knob of the spark gap, and negative electricity will be distributed over the other coating, the coil L and the other knob of the spark gap.

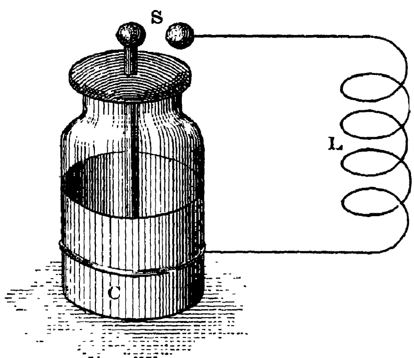

FIG. 14. Leyden jar, inductance coil, and spark gap.

Let V_0 be the difference of potential between the plates of the condenser. Before the current starts there will be the same difference of potential between the knobs of the spark gap, because all parts of a conductor in which no current is flowing are at the same potential.

Let us suppose, now, that the knobs of the spark gap are made to approach each other until the gap is short enough for the potential to start a spark (i.e., about 39,000 volts to the centimeter, if the terminals of the gap are balls 1 cm. in diameter). When the spark starts, the resistance of the gap suddenly drops to a very small value, in some cases to a small fraction of an ohm,[1] and the electric current begins to flow across the gap under the action of the high difference of potential between the plates.

[1] We have seen in Chapter II that a spark is one of those agencies that render gases conductive.

Non-oscillatory Discharge. — If, on the other hand, R^2 is greater than $4\,L/C$, Thomson showed that the discharge is unidirectional; that is, no reversal of the sign of the charge takes place. We should have an analogous condition of affairs with the elastic spring used as an illustration if the bob B (Fig. 12) should be submerged in a liquid, provided the liquid should offer sufficient resistance to the passage of the bob through it. Evidently the amount of resistance required to prevent the oscillation of the bob will increase with increase of the inertia of the bob and with increase of the stiffness of the spring. The former of these corresponds to L, and the latter to the reciprocal of C, so that the fact that L/C will occur in the condition for the oscillation or non-oscillation of the electrical system might have been anticipated.

In the case of the water column, if the connecting tube EF between the two vertical cylinders in Fig. 13 is made sufficiently small to offer enough friction, the motion of the water will also be non-oscillatory. This is analogous to the case of the non-oscillatory discharge of the condenser.

Mathematical Formulas for the Discharge of the Condenser.— Thomson derived the following equations for the current i at any time t, where t is measured in seconds from the time when the discharge begins:

Case I. If $R^2 < 4\,L/C$,

$$i = \frac{2\,V_0}{\sqrt{4\frac{L}{C} - R^2}}\, e^{\frac{-Rt}{2L}} \sin\left\{\frac{\sqrt{4\,LC - R^2C^2}}{2\,LC}t\right\}, \tag{3}$$

in which $V_0 =$ the initial difference of potential,
R = the resistance,
L = the self-inductance,
C = the capacity, and
e = 2.718281 . . . (base of natural logarithms).

This is the case of the oscillatory discharge.

Case II. If $R^2 > 4\,L/C$,

$$i = \frac{V_0}{\sqrt{R^2 - \frac{4\,L}{C}}}\left\{e^{-\frac{t}{T_2}} - e^{-\frac{t}{T_1}}\right\}, \tag{4}$$

it will be evident how the curves are drawn; namely, a table is made of current for different values of time, by the aid of formula (3), and then for each value of time plotted horizontally the corresponding value of current is erected vertically, and through the points so obtained a smooth curve is drawn. This process resembles the method employed by navigators to show the route of a ship. Each day, or oftener, an observation of latitude and longitude is made, and a point is put on the map at the intersection of the given latitude and longitude; and through the points thus obtained at successive observations a smooth curve is drawn, which represents the course of the ship, and from which the position of

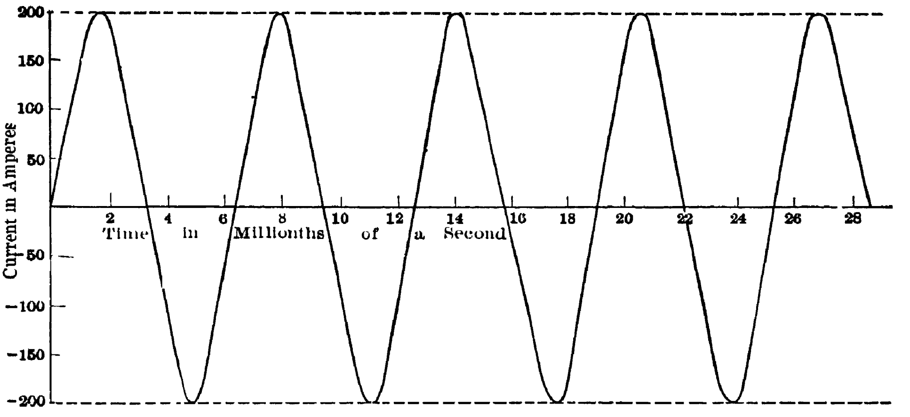

FIG. 15. Current from a condenser of capacity .01 microfarad discharging through an inductance of .0001 henry. Initial potential 20,000 volts. Resistance zero.

the ship at points intermediate between the observations may also be approximately obtained.

Curves Showing Condenser Discharge. — The manner in which the discharge of a condenser occurs under different conditions is represented graphically in the curves of Figs. 15, 16, 17 and 18. In these curves the time in millionths of a second is plotted horizontally, and the current in amperes is plotted vertically. These curves are calculated from the formulas given on page 31. In all four cases the capacity, self-inductance and initial potential are the same; namely, $C = 10^{-8}$ farads, $L = 10^{-4}$ henrys, $V_0 = 20,000$ volts. The only difference between the conditions of the discharge in the four cases is the difference in resistance of the circuit through which the discharge occurs.

In Fig. 15 the resistance is supposed to be zero, and we have

case has also the same capacity, self-inductance and initial voltage as the preceding cases, but the current is seen to rise only to about 75 amperes and then gradually to approach zero.

If the resistance be made greater than 200 ohms, we have Case II, in which the discharge is also non-oscillatory. A curve representing this case is not given; the form of such a curve is somewhat like that of Fig. 18, with the exception that the curve does not rise to so great a value and does not approach zero so rapidly as does the curve in Fig. 18.

The Period of Oscillation. — From equation (3), p. 31, it can be shown that the period of a complete oscillation of the current, in case the discharge is oscillatory, is

$$T = 2\,\pi\,\frac{2\,LC}{\sqrt{4\,LC - R^2C^2}}, \tag{6}$$

in which T is the time of a complete oscillation in seconds; L, C and R are measured in the same set of units; e.g., henrys, farads and ohms respectively; π is 3.1416 . . . , the ratio of the circumference to the diameter of a circle.

Equation (6) is the exact expression for the period, but in most practical cases that occur in the use of electric waves it is found that the effect of the resistance is inappreciable in its effect on the period; that is, in equation (6), R^2C^2 is small in comparison with $4\,LC$, so that the expression for the time of a complete oscillation simplifies to

$$T = 2\,\pi\sqrt{LC}. \tag{7}$$

This formula is usually sufficiently accurate. For example, in the case plotted in Fig. 16, the period of oscillation calculated by equation (7) differs from the exact value, obtained from equation (6), by one-fourth of one per cent

The various formulas given in this chapter were first obtained mathematically by Sir William Thomson in 1855. In 1859 Feddersen demonstrated the oscillatory character of the discharge by a revolving mirror photograph of the spark, similar to the photograph shown in Fig. 3 of Chapter I. Since then all of Thomson's equations have been submitted to careful tests and have been found to be accurate.

that when a condenser is charged, the condition of things is not completely described by saying that a positive charge is given to one plate and a negative charge to the other plate of the condenser. Faraday showed that something takes place in the medium between the plates, and Maxwell makes the assumption that the action in the medium partakes somewhat of the nature of an electric current, although the medium is an insulating substance.

It is difficult to determine just how Maxwell imagined this action to take place, and different writers have employed different mechanisms in the description of the current that Maxwell supposed to exist in the insulators. One way of representing his idea is to suppose that the insulating medium, whether a solid, liquid, or gaseous dielectric, or even empty space, is made up of small parts, and to suppose that the electricity in these small parts of the insulator may flow freely in the small parts but cannot flow from one part to the next. If we call these small parts molecules, we may describe the current in the insulating medium as the act of polarizing the molecules. That is, for example, when the left-hand plate of the condenser in Fig. 19 is charged positively, the positive electricity added to this plate attracts the negative electricity and repels the positive electricity of the neighboring molecules, so that the part of each molecule near the plate becomes negative and the distant part becomes positive. Molecules in this condition are said to be polarized. The layer of molecules so polarized acts on the next layer and produces a similar. polarization, so that in turn the molecules throughout the medium between the plates become polarized.

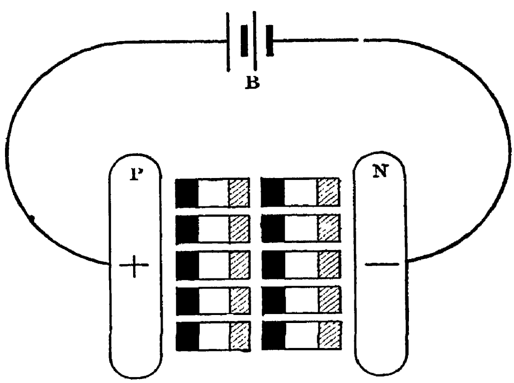

FIG. 19. Illustrating displacement current.

It is seen that this general transfer of positive electricity to the right and negative electricity to the left in the molecules would have an effect similar to an electric current flowing from the positive plate to the negative through the insulator. Maxwell called this general transfer of electricity in the dielectric a *displacement current.* During the charging of the condenser, the displacement current is in the

passes between them. If the resistance is not too large, the current that flows will be oscillatory, because the rods have electrostatic capacity and self-inductance. The two metallic rods here pictured constitute an electric "oscillator."

According to Maxwell's theory, the oscillatory currents in the oscillator will be completed by displacement currents in surrounding space. A part of this displacement current takes place along the black loops in the direction of the arrows from one end of the oscillator around to the other. The displacement loops are really sections of a sheet, such as would be obtained if we rotated the figure

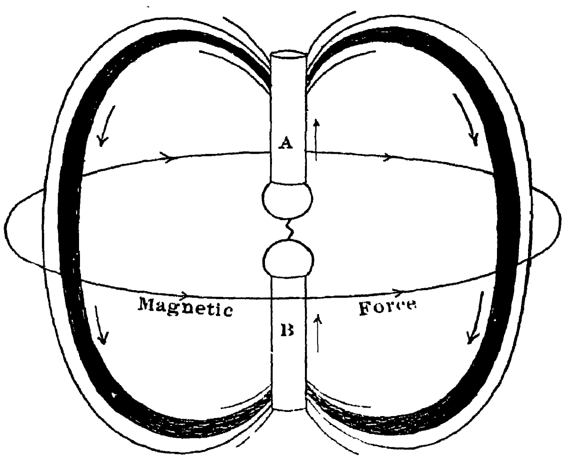

FIG. 20. Displacement current and magnetic force.

about the oscillator as an axis. These displacement currents in the sheet will reverse their direction when the current in the oscillator reverses, and are accompanied by a magnetic field of which a single line is shown encircling the displacement sheet. The magnetic field produced by the displacement current in the shaded region, being oscillatory in character, will induce displacement currents in a portion of the medium farther out from the oscillator, and the latter current will lag somewhat behind the former. Thus, a sheet corresponding to the shaded region will sustain a displacement current oscillating with the period of the oscillator. The unshaded region farther out will sustain similar oscillations a little later, so that we have the condition of things that exists in a wave motion traveling with a finite velocity; namely, a series of disturbances first in one direction, then in the opposite direction, taking place all over a closed surface, and traveling outward from the source.

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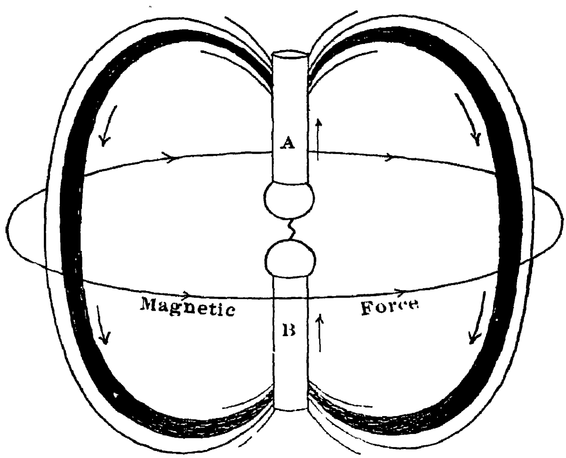

FIG. 20. Displacement current and magnetic force.

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4. All good conductors are opaque to electric waves, all good insulators are transparent to electric waves, and semiconductors like wood and stone are semitransparent. Metallic surfaces are practically perfect reflectors of electric waves.

The Electromagnetic Theory of Light. — Among these several properties of electric waves the properties stated in 1 and 2 are identically true of electric waves and light; while the properties enumerated in 3 and 4 have also met with very useful application to light as well as to longer electric waves. Thus Maxwell came to the conclusion that light waves are electric waves of short wave length. This theory is now generally accepted.

It is interesting to note, on this theory, how light can be produced. We have seen how electric waves may be produced by oscillating electric currents in a circuit of the form shown in Fig. 20. Now if we suppose the oscillator of Fig. 20 to be made smaller and smaller, the capacity and inductance will both be decreased, and the time of oscillation is thereby decreased. If then we think of the oscillator as possessing atomic dimensions, the period of oscillation approaches that of light. It is, however, not necessary to think of an actual electric discharge taking place between the atoms of our atomic oscillator, because the rapid vibratory motion of a single charged particle, or electron, back and forth would have the same effect as an electric discharge between particles, and would produce electric waves of which the period, for a particular size and velocity of the vibrating particle, would be the period of light of some particular color.

Let us turn next to the experimental demonstration of the existence of the electrical waves predicted by Maxwell. This did not come during Maxwell's lifetime; in fact, twenty-two years elapsed between Maxwell's remarkably clear presentation of the theory and Hertz's brilliant confirmation of it.

across the spark gap at S'. The two circuits were then in resonance; that is to say, they had the same period of oscillation as determined

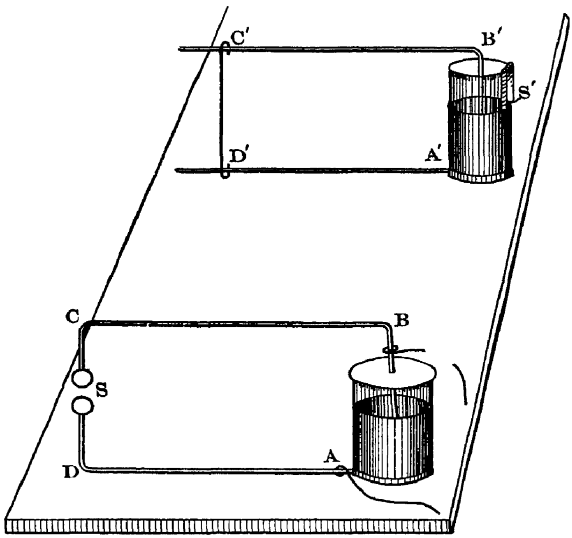

FIG. 22. Sir Oliver Lodge's resonant Leyden jars.

by the formula $T = 2\pi\sqrt{LC}$. The oscillatory current in the discharge circuit induced an electromotive force in the receiving circuit, and when the circuits were in resonance, this induced electromotive force was capable of forcing sparks across the gap at S', even when the two circuits were several meters apart.

According to Maxwell's theory, the inductive action between the two circuits consisted of electric waves sent out from the discharge circuit and striking the receiving circuit; but Lodge was not able to demonstrate the existence of these waves. To do this it was necessary to make the wave length shorter and the radiation freer than that produced by Lodge's discharge circuit.

Hertz's Experiments with Electric Waves in Air. — In order to produce shorter waves than those employed by Lodge, Hertz made use of a discharge system with smaller capacity and self-inductance. One form of Hertz's "oscillator" is shown in Fig. 23. It consists of two flat metallic plates, 40 cm. square, each attached to a rod 30 cm. long. The two rods were placed in the same line, and were provided at their nearer ends with balls separated by a spark gap about 7 mm. long. The oscillator was charged from the secondary of a Ruhmkorff coil J attached to the rods near the spark gap. The

To demonstrate the existence of the electric waves Hertz made use of the phenomenon of interference. The arrangement of apparatus is shown in Fig. 25. M is a metallic reflector, consisting of a sheet of zinc, 2 meters wide by 4 meters high, from which the waves sent out by the oscillator are reflected. The reflected waves superimpose upon the direct waves, producing in the region between the oscillator and the metallic reflector certain positions where the direct and the reflected waves neutralize each other and certain other positions in which their effects add. In demonstrating these effects Hertz performed a number of beautiful experiments.

In one experiment the plane of the resonator was kept parallel to the reflector, with the spark gap at the side, as shown in Fig. 25. Then wherever the resonator may be placed along the line SN_1, the electric force F and F' is the same at the two sides of the resonator. But the force F', being applied to a completely metallic part of the loop, acts to a greater advantage [1] than the force F, so that sparks are produced unless both F and F' are very small. With this orientation of the resonator, Hertz started with the resonator at N_1 close to the reflector and moved it gradually away toward the oscillator.

In the position N_1 there were no sparks in the resonator, showing that there is *a node of electric force* at the reflector. This result is consistent with the fact that a large difference of potential cannot be set up in the surface of a good conductor. As the resonator is moved away from the reflector, sparking begins in the resonator, becomes more and more lively, until a maximum is reached at L_1. This position L_1, is called *a loop of electric force*. On proceeding further in the same direction, a second minimum of sparking is found at N_2, and so forth.

Discussion of this Experiment. — The occurrence of maxima and minima in the region between the reflector and the oscillator is evidence of the undulatory nature of the disturbance, and the distance N_1N_2, or L_1L_2, is the half wave length. To make this proposition clear, reference is made to Fig. 26, which shows several drawings of the direct and the reflected wave and the resultant obtained by their superposition. The reflecting mirror is represented by the heavy vertical line at the right. The undulating line, made up of dashes, represents the direct wave, which is moving toward the reflector; and the dotted wavy line is the reflected wave, moving from the reflector. The heavy line in the

[1] In the same way that plucking a violin string at the middle will produce a greater motion than plucking it near the end.

neutralize each other, while at other points their intensities add. At L_1, L_2 and L_3 the added intensities give a resultant about 1.4 times the maximum of either wave alone.

In (*c*), $t = 2\ T/8$, the direct wave has approached the mirror by another eighth of a wave length, the reflected wave has receded

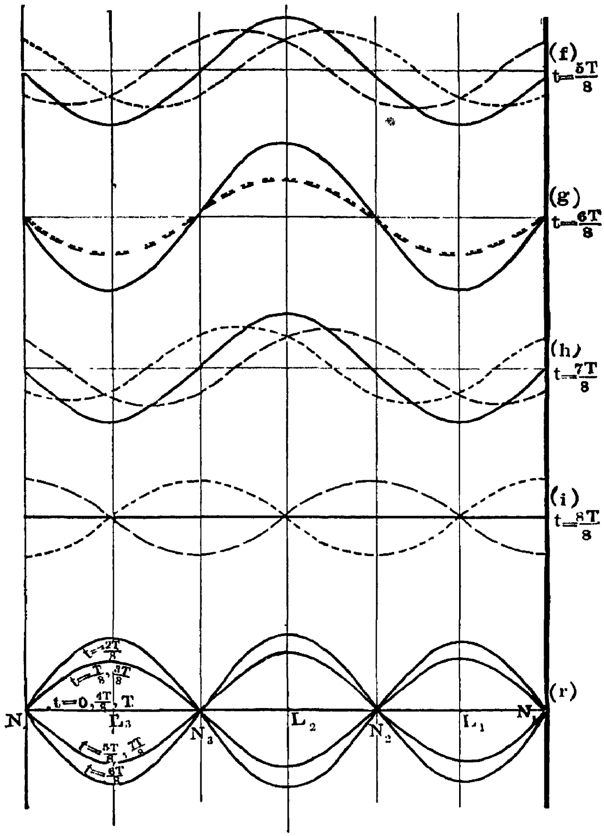

FIG. 26 (Continued).

from the mirror by an equal amount, and the two waves exactly superpose. The resultant intensity of electric force is still zero at N_1, N_2, N_3 and N_4, while at L_1, L_2 and L_3 the intensity is double that of either wave separately.

In a similar manner the remaining drawings (*d*), (*e*), (*f*), (*g*), (*h*), (*i*) represent the progress of the direct wave toward the mirror and the recession of the reflected wave from the mirror by successive eighths of a wave length. The resultant intensity is always zero

either side of the oscillator are shown the lines along which Maxwell's displacement currents occur. These lines are called *lines of electric induction.* We have seen in Chapter VII how we can imagine the displacement current in the dielectric to complete the conduction current in the oscillator. In that case the lines of electric induction terminate on a positive and a negative charge at their two ends. At the instant represented in the diagram, the two halves of the oscillator have opposite charges, and some of the lines of electric induction near the oscillator terminate upon the charges on the oscillator. But a little farther out from the oscillator the lines in the diagram are represented as closed upon themselves. This closing of a loop on itself occurs when the positive and the negative charges on the oscillator come together as the current in the oscillator reverses. The closed loops represented in the diagram have been produced by successive oscillations of the current on the oscillator, and have been liberated from the oscillator and are moving freely away. The condition of things in the space around the oscillator in action may be pictured to the mind by supposing that these closed loops of electric induction move away from the oscillator, and as they move they elongate and grow less intense. Their width, however, remains constant, so that if a receiver be placed in any fixed position, say in the equatorial plane, *PP*, the inductive action of the loops, as they successively pass, changes continuously from one direction to the other with a period equal to that of the oscillator. This train of continuously reversing electrostatic induction is one aspect of the electric-wave train.

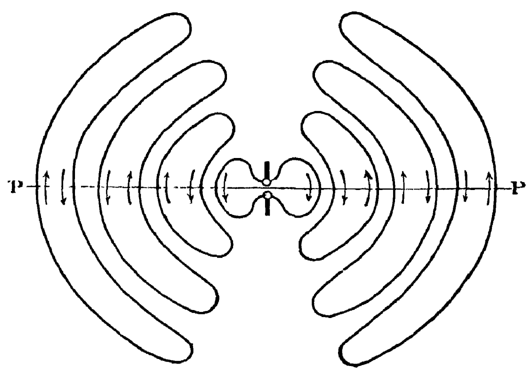

FIG. 27. Simplified diagram of electric force about an oscillator.

Another aspect of the electric wave train may be discovered by examining the magnetic field about the oscillator. The lines of magnetic force about the oscillator are circles in a plane perpendicular to the oscillator, and these lines in a non-magnetic medium are everywhere perpendicular to the lines of electric induction, so

CHAPTER IX

EXPERIMENTS ON THE IDENTITY OF ELECTRIC WAVES AND LIGHT

Hertz's Apparatus for Shorter Electric Waves. — After Hertz had succeeded in proving that the action of an electric oscillation spreads out as a wave into space, he planned experiments with the object of concentrating this action and making it perceptible to greater distances, by putting the oscillator in the focal line of a large concave cylindrical mirror. In order to avoid the disproportion between the length of the waves and the dimensions he was able to give to the

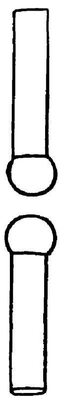

FIG. 28. Hertz's rectilinear oscillator.

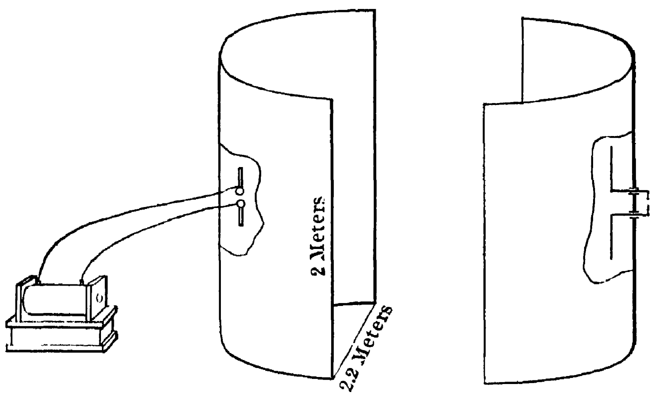

FIG. 29. Hertz's cylindrical mirrors. Oscillator is at left; resonator, at right.

mirror, Hertz made the oscillator smaller, so that the length of the waves was less than one-tenth of those first discovered.

The form of oscillator used in these experiments is shown in Fig. 28. The two halves of the oscillator were cylindrical bodies 3 cm. in diameter, terminating in spheres 4 cm. in diameter. The total length of the oscillator was 26 cm., and the spark gap was usually about 3 mm.

For a receiving circuit, the circle of wire used in the previous experiments was replaced by a linear resonator, consisting of two straight pieces of wire, each 50 cm. long and 5 mm. in diameter, adjusted in a straight line so that their near ends were 5 cm. apart.

the resonator completely, while the two screens in the position B and B' did not materially diminish the sparks at the resonator. If, however, the opening between B and B' was made narrower, the sparks became weaker, and disappeared when the opening was reduced below a half meter. In experiments of this kind, although the dimensions of the screens are measured in meters, these screens are yet not large in comparison with the wave length of the waves, and the phenomena of diffraction are very marked, so that there is no sharp geometrical limit either to the rays or to the shadows.

Polarization. — Hertz showed that the electric waves produced by his linear oscillator are *polarized waves.* One way employed by him for showing this was to start with the focal lines of the two reflectors parallel, as in Fig. 29, so that there is lively sparking at the

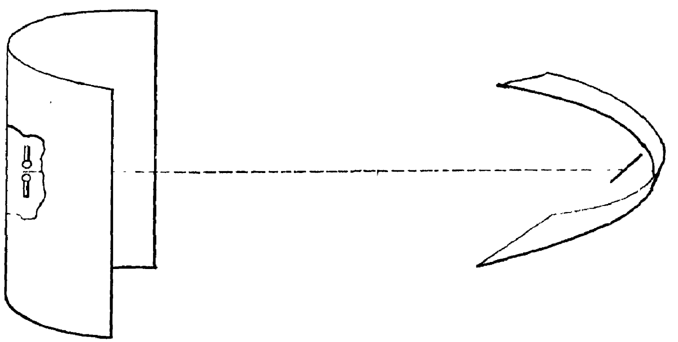

FIG. 31. Showing polarization by the absence of effects when the oscillator and the resonator are at right angles to each other.

resonator, and turn the receiving mirror about the line joining oscillator and resonator. During this operation the resonator sparks become more and more feeble, and when the two focal lines are at right angles, as in Fig. 31, no sparks whatever are obtained at the resonator, even when the two mirrors are moved up close to each other.

In another method of showing that the electric waves are polarized, Hertz made use of a grating of wires. The wires of the grating were 1 mm. in diameter and 3 cm. apart, and were mounted in an octagonal wood frame 2 meters high and 2 meters long. When the grating was interposed between the oscillator and the resonator so that the direction of the wires of the grating was perpendicular to the oscillator and the resonator, as shown in Position 1, Fig. 32, the screen practically did not interfere at all with the sparks at the resonator. But if the screen was set up in such a way that its wires

tion of its wires. This component is inclined at 45° to the axis of the receiver, and so has a component along the direction of the resonator.

From these experiments it is evident that the interposition of the screen stops the waves when the wires of the screen are parallel to

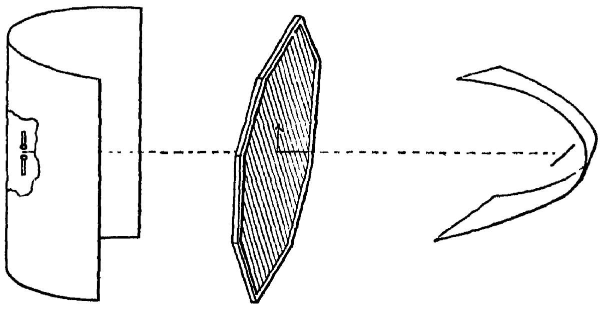

FIG. 33. Rotation of plane of polarization by a wire grating at 45°.

the *electric* component of the waves. It is in this position that the electric force would produce currents in the wires. The changing magnetic force at right angles to the wires would also produce currents in the wires, so that both the components, that is to say, the whole electric wave, would be absorbed or reflected. Hertz showed that the action was one of reflection rather than of absorption; in this the wire screen differs from the action of the tourmaline crystal on light, for the extinguished component in that case is absorbed rather than reflected.

Refraction. — Hertz also performed some experiments on the refraction of electric waves, employing for the purpose a large prism

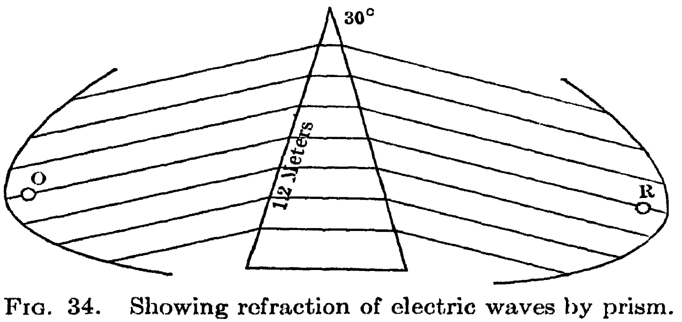

FIG. 34. Showing refraction of electric waves by prism.

of pitch cast in a wooden box. The base of the prism was an isosceles triangle 1.2 meters on the side, and with a refracting angle of

machine used to charge the oscillator. These terminals are provided with the spheres A and D, which are separated from the spheres B and C of the oscillator by spark gaps in air, so that the oscillator BC is without metallic connection with the other parts of the circuit. The spheres B and C were fastened with shellac into the truncated cones of glass EF and GH, which were supported in an ebonite frame. The lower funnel-shaped glass vessel served to contain the oil. The spark length in oil between B and C could be regulated by the screw V. The advantage of having the spark between the spheres take place in oil instead of in air, as had already been pointed out by MM. Sarasin and De la Rive, arises from the fact that it takes a greater difference of potential to start a given length of spark and therefore gives a more energetic discharge. When the spark is once started, the oil is carbonized and becomes conducting, so that the succeeding oscillations pass with comparatively little damping. Also the oil obviates the necessity of repeatedly polishing the terminals, as Hertz found he had to do when he attempted to get short waves with the spark in air. Righi found that vaseline oil is especially well adapted for use with his oscillator.

For a receiving apparatus Righi made use of a resonator consisting of a strip of silver AB deposited on glass and interrupted by a diamond scratch C across the middle of the strip. This provided an extremely short spark gap between the two parts of the resonator, as shown in Fig. 36. Also the spark across this small gap will occur more easily than a spark of equal length in free air.[1] Righi's resonator is thus seen to be an extremely sensitive modification of the rectilinear resonator used by Hertz.

In most of Righi's experiments the oscillator and the resonator were mounted in cylindrical reflectors. The mounting of the resonator is shown in section in Fig. 37. The resonator is at A, and is fastened upon a strip of ebonite BC. The observer looks through the converging lens at H, which serves to magnify the minute sparks between the two halves of the resonator. The apparatus could be used quantitatively by observing the angle through which it was necessary to turn the resonator and its reflector in the support LM in order to extinguish the sparks. The angle of turning was indicated by the pointer N moving over a graduated circle OP.

[1] The author has shown that the potential required to start a spark along a surface of glass is about .44 of the potential to start a spark of equal length in free air. (Pierce: Physical Review, Vol. 2, p. 99, 1894.)

Ignaz Klemenčič [1] showed that a thermal junction could be employed to detect and measure the waves. Klemenčič's device, Fig. 38, consists of two thin sheets of brass *MM*, 10 cm. broad and 30 cm. long, placed 3 cm. apart, and having soldered to them respectively a very fine platinum and a very fine platinum-nickel wire, which were crossed at *k* and were thence conveyed off at right angles and soldered at their other ends to the leads *l*, *l* of a sensitive galvanometer. This resonating system was fixed at the focal line of a suitable cylindrical metallic reflector. When electric waves, with the electric force parallel to *MM*, fall on this receiver, electric oscillations between *M* and *M* produce heating of the knot *k*, which is the point of contact of two dissimilar metals, and in consequence the heat developed gives rise to a thermoelectromotive force at the knot and consequently to a current in the galvanometer. By the use of this instrument and a Righi oscillator, Klemenčič has studied the reflection of electric waves from metals and insulators.

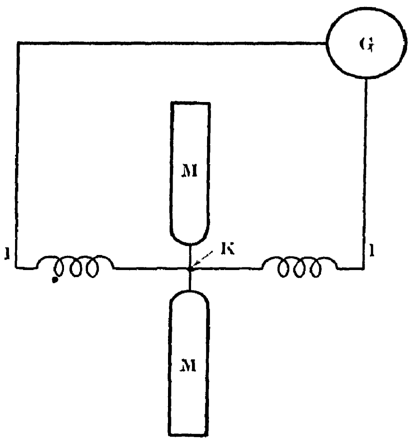

FIG. 38. Resonator employing thermal junction.

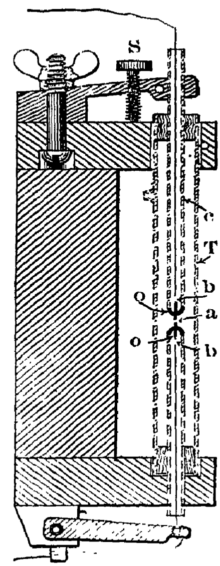

FIG. 39. Oscillator for very short electric waves.

Various investigators have made use of the Klemenčič thermal junction in quantitative experiments on electric waves. By reducing the size of the metal vanes *MM*, Professor A. D. Cole [2] has applied the apparatus to measurements with waves with a wave length of 4 cm. Professor Lebedew,[3] employing a slightly different form of

[1] Ignaz Klemenčič: Wied. Ann., 45, p. 62, 1892.
[2] A. D. Cole: Wied. Ann., 57, p. 290, 1896, and Phys. Review, 7, Nov., 1898.
[3] Peter Lebedew: Wied. Ann., 56, p. 1, 1895.

radiations than these are to the ultra-violet or even to the visible. For example, some of the long heat waves, like the Hertzian waves, pass readily through vulcanite and other insulators opaque to visible light.

Space is lacking to consider further the experimental evidence in favor of Maxwell's proposition that electric waves are of the same nature as light waves, and that the light waves are in fact simply electric waves of those particular wave lengths that possess the property of being capable of affecting the retina of the eye.

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current, and for this purpose availed themselves of the telegraph lines between Paris and Amiens (314 kilometers) and between Paris and Rouen (288 km.). Their measurements gave a velocity of 101,700 km. per second for iron wires, and 172,000 km. per second for copper wires.

In other similar measurements of the apparent velocity of the electric current various results have been obtained in practice which are much lower than those of Wheatstone, and Fizeau and Gounelle, being in some cases 2240 kilometers per second, and in others 4800, 28,000, 96,000 and so on. What, then, is the explanation of this great variability in the experimental results?

Theoretical Discussion. — In 1855, in discussing the feasibility of an Atlantic cable, Sir William Thomson gave a mathematical treatment of a case of the propagation of electric disturbances in conductors. In 1857 Kirchhoff, and in 1876, Heaviside, developed extended theoretical treatments of the problem. The results obtained by these mathematical physicists show that the velocity of propagation of electrical disturbances in conductors depends on the nature of the disturbance and the relative values of the capacity, self-inductance and resistance of the conductor.

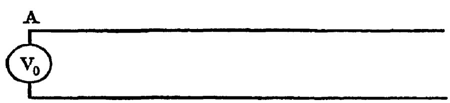

FIG. 40. Two parallel wires with applied electromotive force.

If we have two long parallel wires (Fig. 40) as in the case of land telegraph and telephone lines, or one wire in an insulating sheath submerged in a conducting body, as in the submarine cable, three important cases arise in practice.

Case I. Telegraphy. — If the self-induction of the line is negligible in comparison with its resistance and we have an electromotive force impressed on one end of the line, the current in the conductor grows in a manner described as "diffusion." Fig. 41 gives a set of curves [1] showing the difference of potential between the two conductors at various positions along the line, at different times after the application of the electromotive force. In this case there is no proper velocity of the electricity; for at the instant the battery is applied some electricity appears all along the line, and the charge at a short distance from the origin grows faster than the charge at a greater distance. This is approximately the case that occurs in submarine

[1] Redrawn from Professor A. G. Webster's Electricity and Magnetism; Macmillan, 1897.

than for a slow application of the charge. For this reason the propagation of the disturbance is more accurately represented by the set of curves given in Fig. 42. In this diagram it is seen that the disturbance has a nearly square wave front, which, according to the theory, travels with the velocity of light, while succeeding parts of the impulse lag more and more behind the wave front. The square wave front itself becomes also more and more attenuated as the disturbance progresses along the wires.

This same condition of things exists to some extent in the case of land telegraph lines, and accounts for the indefiniteness of the results that have been obtained in the attempt to measure the velocity of propagation. If for a particular length of line the apparatus used by the experimenter for detecting the wave is sufficiently sensitive to respond on the arrival of the wave front, the value obtained for the velocity is the velocity of light; while with a greater length of line the wave front is too feeble to affect the instrument, which then responds to a more intense part of the wave arriving later, and hence gives a smaller value for the velocity.

Case II. Telephoning. — Suppose, now, that instead of simply applying a battery to the line, as in telegraphing, we apply a *telephonic* electromotive force to the parallel wires of Fig. 40 or to the submarine cable. This telephonic electromotive force is an alternating electromotive force. Although the self-inductance and resistance of the circuit may be the same as before, the effect of the self-induction is larger in the telephonic case, because of the rapidity of the alternations of the electromotive force at the source. Under this condition Heaviside finds that the different waves generated by the sounds of different pitch travel with different velocities, and that this results in a distortion of the wave and puts a limit to the distance to which the telephone can be used. This distortion is caused by the resistance and capacity of the line, and is partially eliminated by self-induction. Heaviside says that this "self-induction is the telephonist's best friend," for it tends to preserve the sharpness of the wave and to eliminate the part of the disturbance lagging behind the wave front. Heaviside pointed out that the addition of properly distributed self-induction was *beneficial* to prevent distortion in telephony; and in actual practice, by adding inductance coils at intervals along telephone lines, Professor Pupin has considerably increased the distance to which distinct speech may be transmitted.

In the case of the submarine cable, on account of the relatively small value of the self-inductance, submarine telephony is not at

cannot flow past the end of the wire, nor does the electricity constituting the current merely flow out to the end of the wire and stop in a state of equilibrium. Two forces are acting on the current: (1) the accumulation of electricity near the end of the wire raises the potential of the wire and provides a force opposing the current; (2) the slowing down of the current causes change in the magnetic field surrounding the wire, and this tends to prevent the cessation of the current. These two forces do not act together,— when one is a maximum, the other is a minimum. As a result first one and then the other of these forces will predominate, so that the charge will first be sent into the parts near the end of the wire by the magnetic field (self-induction) and will then be sent out again by the electrostatic rise of potential (reciprocal of capacity). The effect of this is that the periodically arriving impulses will be sent back again with the same period, and we shall have, therefore, a direct and a reflected train of waves. The direct and the reflected waves will interfere with each other, so as to form a stationary system of waves like that obtained in the experiment with waves in air reflected from a sheet of metal (Chapter VIII). In this case, however, the end of the wire will be a loop of potential; whereas the metal reflector of the waves in air is a node of potential. There is also another difference; for in the case of the wire, the returning wave will again be reflected at P, and a simple stationary wave system can only be realized provided the horizontal wire has a proper length, which may be determined by experiment.

Hertz studied the waves produced in the wire, with the aid of his circular resonator, shown in the figure. With the resonator in the vertical position C, Hertz was able to locate the nodes and loops of current in the wire by the absence or presence of sparks at the resonator. When, however, the resonator was placed in the horizontal position B, the effect obtained was due partly to the waves in the wires and partly to a linking with the resonator of magnetic lines directly from the oscillator. The compound effect obtained in the latter case was utilized by Hertz in a study of the interference between the waves in the wire and the waves in the air. He came to the conclusion that the wave length, and consequently the velocity of propagation, was different in the two cases. This was in contradiction of Maxwell's theory.

Later, by the use of a smaller oscillator at AA', he found that the difference between the velocities of the waves on wires and in air very nearly disappeared.

a resonance method, like that at the present day used in getting the wave length in a wireless telegraph antenna.

The following results were obtained for the velocity of electric waves on wires:

Observer.	Velocity in kilometers per second.
Blondlot	293,000 298,000
Trowbridge and Duane. ...	298,800 300,300
Saunders	295,400 299,400 299,800 299,800 299,500 299,900

The average of the best determination of the velocity of light is about 299,900 kilometers per second, with which the above determinations of the velocity of the electric waves on copper wires is in good agreement.

Velocity of Electric Waves in Air. — Although the velocity of the electric waves in air has not been determined by a direct method, the experiment of Sarasin and De la Rive showed that the velocity of the waves in air is the same as their velocity in copper wires surrounded by air, and therefore the same as that of light.

Waves on Iron Wires. — On account of the magnetic properties of iron, the velocity of the waves on small iron wires has been found to be slightly less than the velocity of waves of the same period on a nonmagnetic metal like copper. With wires $\frac{1}{2}$ millimeter in diameter and with 115,000,000 oscillations per second, St. John found that the velocity on the iron wire was 4 to 5% less than the velocity on the copper wires. This result showed that the magnetization of the iron is able to follow extremely rapid reversals of the magnetizing current.

On Surface Travel. — In addition to this slight change in velocity due to the magnetic property of the iron, the damping effect of the resistance of the iron is very large. In attempting to estimate the effect of resistance on the damping of oscillations of high frequency, it should be remembered that these rapid currents travel in a very thin film on the outside of the conductor. By

and $A'B'$ and the spark gap F. This circuit has its own definite period of oscillation. The other circuit, which we will call the "resonator circuit," consists of the conductors $gXX'g'$. When the bridge XX' is in the position that causes the Geissler tube to glow, the oscillator circuit and the resonator circuit are in resonance, and during one complete oscillation the electric wave goes from the bridge out to g', back across the bridge, out to g, and back again to the bridge. Whence it is seen that the length of the conductor from g' across the bridge to g is the half wave length of the oscillator.

If now the bridge is moved from XX' toward the oscillator, a second position SS' of the bridge is found for which the tube is caused to glow. During this displacement of the bridge, the self-inductance, and therefore the period, of the oscillator circuit is diminished, while the length of the wire to the right of the bridge is increased. Therefore, the wire to the right of the bridge cannot be in resonance, as a whole, with the oscillator circuit. We can show this experimentally, for if we leave the first bridge at SS' and place a second bridge across the wires, a position TT' can be found for which the presence of the second bridge does not affect the glow of the tube. A slight motion of the second bridge to the right or to the left diminishes the glow.

The two positions SS' and TT' are called nodes of electric potential. In a similar way with longer parallel wires several nodes may be located. The free end of the wires is always a loop of potential, and other loops of potential exist halfway between the nodes. The presence of these nodes and loops at equal intervals along the parallel wires shows the existence of a stationary wave system similar to that discovered by Hertz in his experiments with electric waves in air.

Blondlot's Apparatus. — A modification of Lecher's apparatus made by Professor Blondlot is shown in Fig. 45. The two halves of the oscillator are here bent into semicircles, while the parallel wires lead out from a secondary circuit placed immediately beneath the oscillator. The oscillator and the circular portion of the secondary are submerged in a glass vessel containing oil. Leads from the induction coil are brought into the oil and connected to the two sides of the spark gap, — one connection being made directly at a and the other connection being through a small spark gap at b. In this form of apparatus the waves on the wires are produced by electromagnetic induction from the oscillator.

In Paalzow and Rubens's arrangement of apparatus (Fig. 48), in order to avoid disturbing the waves on the wires *PQRS*, the leads to the bolometer were not connected directly to the wires under examination, but were connected inductively by a single turn around capillary glass tubes *TT*, sliding on these wires. The glass tubes *TT* act as diminutive Leyden jars with the horizontal wires inside the tube for one coating, and the turn of wire on the outside of each tube for the other coating. Variations of electric potential at a point inside the little tubes induce (by electrostatic action) alternating potential in the turns of wire outside and produce alternating currents through one arm of the bolometer bridge.

Figure 48 shows a form of apparatus suitable for experiments with this method. This is the form of apparatus used by Professor

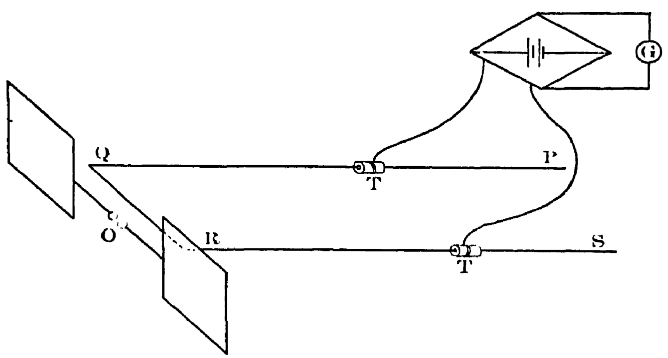

FIG. 48. Exploration of waves on wires by bolometer.

St. John. As has been before mentioned, in order to get a simple stationary wave system in the parallel wires, these wires must have a proper length in comparison with the wave length of the waves. In St. John's experiment the proper length of the wires was determined by trial. The exploring terminals of the bolometer were put at the ends *P* and *S* of the wires of Fig. 48. The oscillator was set in activity, and a reading of the bolometer was taken for this length of wire. A few centimeters of wire were cut off, and the reading again taken. This process was repeated until a maximum point was passed. A sharp and unmistakable maximum was found when *PQ* had a certain length (859 centimeters). The effect fell off rapidly when the wires were shortened or lengthened from this point. The result is shown graphically in Fig. 49,

CHAPTER XI

WIRELESS TELEGRAPHY BEFORE HERTZ

By Conduction through Water. — The first successful attempt at electric telegraphy[1] between stations not connected by wires seems to have been made by S. F. B. Morse in 1842. Morse describes his experiments in a letter to the Secretary of the Treasury of the United States, which was laid before the House of Representatives on December 23, 1844. He says:

"In the Autumn of 1842, at the request of the American Institute, I undertook to give the public in New York a demonstration of the practicability of my telegraph, by connecting Governor's Island with Castle Garden, a distance of a mile; and for this purpose I laid my wires properly insulated beneath the water. I had scarcely begun to operate, and had received but two or three characters, when my intentions were frustrated by the accidental destruction of a part of my conductor by a vessel, which drew them up on her anchor, and cut them off. In the moments of mortification I immediately devised a plan for avoiding such an accident in the future, by so arranging my wires along the banks of the river as to cause the water itself to conduct the electricity across. The experiments, however, were deferred till I arrived in Washington; and on December 16, 1842, I tested my arrangement across the canal, and with success. The simple fact was then ascertained that electricity could be made to cross the river without other conductors than the water itself; but it was not until the last Autumn that I had the leisure to make a series of experiments to ascertain the law of its passage. The following diagram will serve to explain the experiment:

"*A*, *B*, *C*, *D* (Fig. 51) are the banks of the river; *N*, *P*, is the battery; *G* is the galvanometer; *ww*, are the wires along the banks connected with copper plates, *f*, *g*, *h*, *i*, which are placed in the water. When this arrangement is complete, the electricity, generated by the battery, passes from the positive pole *P*, to the plate *h*, across the

[1] A large part of the historical information contained in this chapter was obtained from Mr. J. J. Fahie's excellent History of Wireless Telegraphy, Dodd, Mead & Co., 1902.

telephone in the circuit. In the first boat, which was moored, I kept a man making signals; and when my boat was near his I would hear those signals very well — a musical tone, something of this kind; tum, tum, tum. I then rowed my boat down the river, and at a distance of a mile and a quarter, which was the farthest distance I tried, I could still distinguish those signals."

In these experiments of Morse, Lindsay, Trowbridge and Bell the signals were carried from one station to the other by conduction through the water. The current in flowing from one submerged plate to the other at the sending station spreads out through the water in curves like those of Fig. 52. If, now, the terminals of the receiving circuit dip down into the conducting area, the current divides,—part going through the water and part through the receiving circuit, in the inverse ratio of their resistances. This method of signaling, though attempted with improved apparatus by Messrs. Rathenau, Rubens, and Strecker, and by the latter carried to a distance of 14 kilometers (8.7 miles), has not contributed to the art of wireless telegraphy, as it is now practiced.

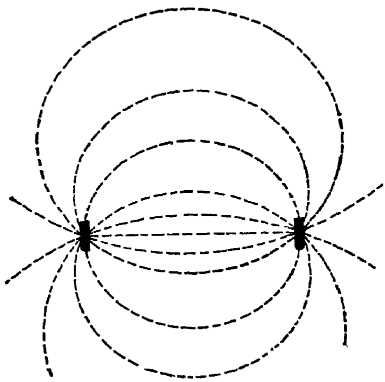

FIG. 52. Lines of flow.

Dolbear's Apparatus.—A somewhat more suggestive apparatus was invented by the late Professor Dolbear of Tufts College, Massachusetts, and was awarded a United States patent in March, 1882. Figure 53, taken from the patent specifications, shows a diagram of the apparatus. The transmitting station, shown at the left, consisted of a condenser H' connected to one terminal of the secondary of an induction coil G, of which the other terminal of the secondary was grounded at C. The primary of the induction coil contained a battery f' and microphone transmitter T. The receiving apparatus, shown at the right, consisted of a telephone receiver R with one terminal connected to ground at D, and the other terminal connected to a condenser H, which was in turn connected through a battery [1] B with a second condenser H^2.

Professor Dolbear, in his patent specifications, describes the action of the apparatus as follows:

"Now if words be spoken in proximity to transmitter T, the vibra-

[1] The function of this battery is not evident.

Marconi had made the way clear, was made by Sir William Preece, engineer-in-chief of the postal telegraph system of England. Preece attempted to utilize the electromagnetic induction between two long horizontal wires, one at the sending station and the other at the receiving station. These horizontal wires were supported parallel to each other on telegraph poles, and were grounded at their two ends. The sending wire contained a battery and an interrupter, or else an alternating current generator, so that the line was traversed by an interrupted or an alternating current; while the receiving circuit contained an ordinary telephone receiver. The surging current in the sending wire produced a variable magnetic field surrounding it. This variable magnetic field produced by the sending circuit cut or linked with the receiving circuit, and induced a periodic electromotive force in it, which was evidenced by sounds in the receiver.

After several years of experimenting, Sir William Preece was able to utilize this apparatus for signaling to some of the islands a short distance off the coast of England, and in 1898 a regular installation was established at Lavernock Point on the mainland and at Flatholm in the Bristol Channel, 3.3 miles (5.2 kilometers) apart.

Preece's experiments can be said to have availed only to show the futility of the attempt to get inductive action at long distance without the use of *oscillations of high frequency.*

many interesting experiments in the effort to obtain an explanation of its action. Branly's radioconductor is now familiarly known as the "coherer," — a name invented by Sir Oliver Lodge.

Coherer Applied to Study of Electric Waves. — In 1893 and 1894 Sir Oliver Lodge applied the coherer to the study of electric waves by putting it in the place of the micrometer spark gap in a Hertz resonator, as is shown in Fig. 54. Under the action of the electric waves sent out from a properly placed Hertz oscillator, the resistance of the metallic filings in the coherer fell to a low value, so that the galvanometer *G* connected in series with a battery *B* in a local circuit through the coherer gave a deflection. After the waves ceased the resistance of the coherer remained low, so that the galvanometer remained deflected. In order to prepare

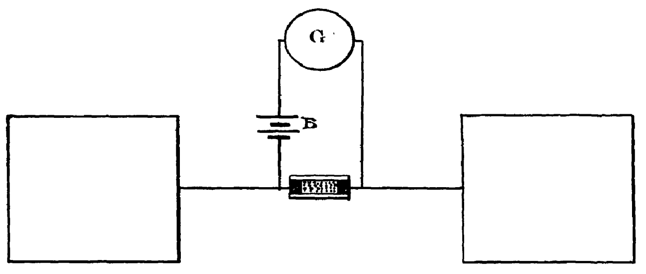

FIG. 54. Sir Oliver Lodge's apparatus for detecting electric waves.

for another reading it was necessary to restore the filings to high resistance by tapping the tube. Lodge effected this restoration either by a tapping mechanism driven by clockwork, or by an electric trembler (like an electric bell) mounted on the same base as the coherer.

With this apparatus Professor Lodge succeeded in detecting Hertz waves at a distance of about 55 yards from the source.

Experiments of Popoff. — A still nearer approach to an operable form of receiving apparatus for wireless telegraphy was made in 1895 by Professor Popoff of Kronstadt, and a description of the apparatus was communicated by him to the Physico-Chemical Society of St. Petersburg in April of that year. Popoff's apparatus, which was designed for use in the study of atmospheric electricity, is shown in the diagram of Fig. 55. The left-hand terminal of the coherer was connected to a metallic rod extending above the house-top; the right-hand terminal of the coherer was connected to earth; so that electric currents produced by the atmospheric elec-

Marconi's 1896 Apparatus. — We come now to the early work of Marconi. After having made some preliminary experiments on his father's estate near Bologna in Italy, Signor Marconi went to England, and on June 2, 1896, filed in the Patent Office of Great Britain a part of his first application for a patent for "improvements in transmitting electrical impulses and signals, and in apparatus therefor." The part of the application filed at this date is without diagrams, and contains only *provisional specifications*. A *complete specification* covering the same subject matter, amply illustrated with drawings and full of details as to the invention, was filed March 2, 1897. This patent application of Mr. Marconi contains the first published account of a completed apparatus for successful wireless telegraphy by electric waves, and is, therefore, a document of considerable interest. It would seem to be not unprofitable to give careful attention to Marconi's description of his invention.

In the description that follows, the quotations are taken from the Marconi patent specifications; and after some of the paragraphs of quoted or paraphrased description I have added a brief paragraph in the form of a summary.

Hertz or Righi Oscillator and Receiver. — At the transmitting station he employs "a Ruhmkorff coil having in its primary circuit a Morse key for starting or interrupting the current." The secondary of the coil he connects to "pole appliances" for producing the desired oscillations. Under "pole appliances" he mentions "insulated balls separated by small air spaces or high vacuum spaces, or compressed air or gas, or insulating liquids kept in place by a suitable insulating material, or tubes separated by similar spaces and carrying sliding discs."

This form of the transmitting apparatus, as may also be seen by reference to the original drawings, is an ordinary Hertz or Righi Oscillator, actuated by a Ruhmkorff coil with a Morse key in its primary circuit. There is, however, also the suggestion of the use of a high vacuum or compressed air or gas about the spark gap.

"At the receiving instrument there is a local battery circuit containing an ordinary receiving telegraphic or signaling instrument and an appliance for closing the circuit." The appliance for closing the circuit "consists of a tube containing conductive powder, or grains, or conductors in imperfect contact, each end of the column of powder or the terminals of the imperfect contact or conductor being connected to a metallic plate of suitable length so as to cause

have shown that the earthing of the circuits, though a convenience in construction, is not essential.[1]

It was with these earthed circuits that Marconi made his first great gains in the distance of transmission; but as we now look back over the experiments, we see that the gain in distance came about primarily through the fact that with this apparatus his circuits were placed vertical rather than horizontal, and also through the use of longer waves and more energy and larger radiating and receiving antennæ, rather than through the use of the mere earth connections. To this subject we return in Chapter XIV.

Marconi's Coherer. — In addition to the practical introduction of the vertically placed radiator with ground connection Signor Marconi also made tremendous progress over other early investigators in his skill in constructing and using the coherer. A sketch of the coherer, drawn natural size from Marconi's specifications, is shown in Fig. 58. The metal plugs *PP* are of silver slightly amalgamated with mercury, but no excess of mercury in the form of globules is left on them. The plugs fit accurately into a glass tube, and are within $\frac{1}{30}$ inch of each other. The filings in the space between the plugs are preferably 96% nickel and 4% silver, and should not be fine, but rather coarse. They should be dry and free from grease and dirt, and should be uniform in size. The tube containing the filings is preferably exhausted of air and sealed up. In sealing up the tube care should be taken not to oxidize the filings. In order that the coherer may not be injured by the current through it, not more than $\frac{1}{1000}$ of an ampere of current should be used in the local circuit.

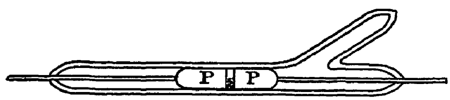

FIG. 58. Marconi coherer (natural size).

Marconi's Decohering Device.—One of the greatest difficulties to be overcome in operating a delicate coherer arises from the fact that the signal causes the coherer to become conductive, and if left alone, the coherer perseveres in this conductive condition. In order to restore it to its high resistance so as to be ready for the next signal, it is necessary to employ an automatic tapper, or trembler, which is started into action by the incoming impulse, and which stops the signal and itself when the incoming impulse ceases. Signor Marconi brought the decohering device to a high state of perfection, and as a result changed the capricious tube of filings into a reliable instrument for practical use.

[1] See Chapter XIV.

spark. We have thus in our supposed case 100 sparks a second. Each spark occurs with oscillations of very high frequency and produces a train of electric waves. With such a sending station we should have arriving at the receiving station a train consisting of a few [1] of these extremely rapid waves, followed $\frac{1}{100}$ of a second later by a second similar train; and thus at intervals of $\frac{1}{100}$ second there would arrive successive short trains of waves while the sending key is depressed.

Under the action of these trains of incoming waves the filings in the tube cohere, so that a current flows from the battery B_1 (Fig. 59) through the coherer *Co* and the relay *R*. This battery current pulls the armature of the relay so as to close the gap at *A*. When the gap is closed a second battery *B* sends a current through the coils of the sounder *S*, and also through the coils of the trembler *T*. The trembler is like an electric bell (with a somewhat shorter striking arm), and makes a series of strokes against the tube of the coherer. This decoheres the filings, but so long as the key at the sending station is closed, the waves continue to arrive and cause a repetition of the coherence, thus putting the coherer in a state of repeated coherence and decoherence during the arrival of the waves. The armature of the relay is adjusted so that the relay is somewhat sluggish and does not open at each decoherence. Therefore, the contact of the relay remains closed, and consequently the sounder armature stays down as long as the trains of waves continue to arrive. When, however, the sending key is released, and the waves cease to arrive, the decoherence due to the tapper perseveres, the relay contact opens, the sounder arm is released, and at the same time the trembler stops. Thus each closing and opening of the key at the sending station produces a corresponding down and up stroke of the sounder, making a dash or a dot, according as the sending key is depressed for a long or a short interval of time.

Instead of the sounder for translating the message an ordinary Morse registering tape-machine may be used to give a written record of the dashes and dots.

Marconi's Protective Resistances and Inductances. — Returning now to diagram Fig. 59, let us examine into the purpose of the resistances p, p_1, q, q', and h, represented by the dotted lines.

[1] I have taken revolving-mirror photographs of the spark of a Marconi Oscillator with a period of $\frac{1}{1000000}$ second, and found that there are about 12 waves in a train.

Balloons or Kites. — Another important suggestion contained in the 1897 specifications is the suggestion that "the larger the plates of the receiver and the transmitter, and the higher from the earth the plates are suspended, the greater is the distance at which it is possible to communicate at parity with other conditions." "Balloons can also be used instead of plates on poles, provided they carry up a plate or are themselves made conductive by being

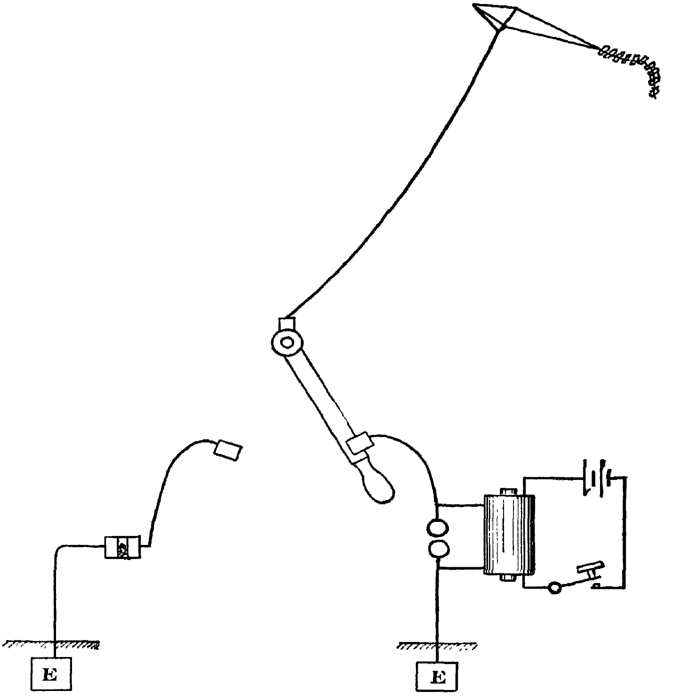

FIG. 60. Simple Marconi circuits with antenna sustained by a kite. Switch for "cutting over" from sending to receiving.

covered with tinfoil. As the height to which they may be sent is great, the distance at which communication is possible becomes greatly multiplied. Kites may also be successfully employed if made conductive by means of tinfoil." This sentence, therefore, provides for the use of antennæ of great height. It should be noted here that the plates or tinfoil covering on the balloons or kites, which the inventor makes a necessary provision of the apparatus, are really nonessential.

A diagram of circuits in which kites are used for suspending the vertical wires is shown in Fig. 60.

Marconi's Achievements between 1896 and 1898. — In July, 1896, soon after arriving in England, Mr. Marconi submitted his plans to Sir William Preece, director of the postal-telegraph system of England. Preece, of whose activity in connection with attempts at wireless telegraphy we have already learned, entered eagerly into the new experiments.

The first messages were sent from a room in the General Post Office to an impromptu station 100 yards distant. Soon afterwards, at Salisbury Plain, with parabolic reflectors about the instruments, communication was established at a distance of two miles. In May, 1897, discarding the reflectors and using grounded circuits, Mr. Marconi covered a distance of 8.7 miles between Lavernock Point and Brean Down. Kites were employed in this experiment to support the vertical wires.

In July, 1897, important trials were made at Spezia, Italy, at the request of the Italian Government, and communication was established at a distance of 12 miles between a warship and a shore station.

In July, 1898, the Marconi apparatus was used to report the yacht races at the Kingston Regatta, and a large number of correct messages were exchanged between a press boat and the shore at distances extending up to 20 miles.

These various experiments constituted a complete demonstration of the utility of the invention.

A Simple Variable Circuit. — A simple method of easily varying the period of a receiving circuit consists in the use of a variable inductance L (Fig. 62), inserted between the detector and the antenna or between the detector and the ground at the receiving station. Such a variable inductance, or tuning coil, is made of a single layer of wire wound on an insulating tube of glass or ebonite, and is varied by a contact sliding along the coil so as to put more or fewer turns of inductance into the circuit. A similar tuning coil, though usually of larger wire, may be used at the sending station also. At the sending station the coil is inserted between the spark gap and the antenna or between the spark gap and the ground connection.

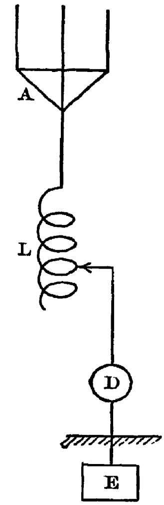

FIG. 62. Simple antenna circuit having a variable inductance for tuning.

Increase of inductance in either circuit increases the time of vibrations, which brings a corresponding increase of wave length.

The use of adjustable inductances in both the sending and the receiving circuits was apparently first suggested by Sir Oliver Lodge in a patent application of 1887, which is reviewed later in the present chapter.

Coupled Circuits. — Certain other methods, employed for adjusting both the sending station and the receiving station, and found to produce better results both for transmitting with large quantities of energy and for receiving with comparatively sharp resonance, make use of *coupled circuits*. The resonance relations in these coupled circuits has been the subject of much theoretical and experimental research. As introductory to the description of the coupled circuits, I shall recall to the reader the familiar and interesting experiments of Mr. Tesla and of Professor Thomson on the production of electric oscillations of high frequency and high potential.

High-frequency Transformers of Thomson and Tesla. — The high-frequency transformer that was apparently independently developed by Mr. Nikola Tesla and Professor Elihu Thomson about 1890 is shown in sketch in Fig. 63. A primary coil P, consisting of one or two turns of heavy wire, is connected in series with a bank of Leyden jars C and a spark gap G. A secondary coil S, consisting of three or four hundred turns of wire wound in a single layer on a paper or vulcanite tube, is inserted axially within the primary. When the

circuit and the secondary coil shall be in resonance with each other.

By the use of apparatus of this character Mr. Tesla has produced enormous sparks — twenty-three feet long and of great volume — graphically described as being accompanied by a roar like Niagara.

The transformer PS is called *a high-frequency transformer, an oscillation transformer,* or *an air-core transformer,* to distinguish it from an ordinary iron-core transformer, such as is used with commercial alternating currents of slow frequency.

Oscillation transformers, built on somewhat different lines from the one above described, have met with application to both the sending and the receiving circuits of electric-wave telegraphy, and by the use of these transformers a considerable advance has been made, both in the greater distances attained and in the diminished confusion of signals of different wave lengths.

Two Systems of Coupled Circuits. — The form given to these coupled circuits is considerably varied in practice. There are, however, two important general types. These are represented in the accompanying figures (Fig. 64 and 65) and are called respectively the *inductively coupled* and the *direct coupled* types.

The Inductively Coupled Type. — This type is shown in Fig. 64. In this system the sending station, shown on the left, is seen to consist of a Tesla high-frequency apparatus, with one secondary terminal connected to an antenna and the other secondary terminal connected to the ground. Power is supplied to the circuit by an alternating current transformer or a Ruhmkorff coil to which the wires W, W'' lead.

The receiving station of this system, shown at the right in Fig. 64, has also an oscillation transformer $P' S'$, and is in principle like the sending station, except that the detector D' with its accessories is usually put in place of the spark gap of the sending apparatus. The coils P' and S' and condenser C' used with the receiving apparatus generally have different inductances and capacity from those of the sending apparatus, and not being traversed by high-potential currents they are usually made more compact.

In this inductively coupled system of circuits, oscillatory currents in the sending antenna are produced inductively by the oscillatory discharge of the condenser C through the primary coil P. These oscillatory currents in the sending antenna produce

system employs auto-transformers; that is to say, instead of having separate primary and secondary coils in the high-frequency transformer, the primary coil (P or P') at either station is a part of the secondary coil. At the sending station (at the left) the condenser discharges through some of the turns of the secondary, and the discharge acts inductively on the whole of the secondary. Likewise, at the receiving station the oscillations in the antenna pass through a part P' of the secondary S' and act inductively on the whole of S'. Theory and experiment show that in principle the direct coupled circuits differ very little from the inductively coupled system.

Introduction of Coupled Circuits into Practice. — Postponing for a time the direct discussion of the principles involved in the use of the coupled circuits, let us take up historically the matter of the introduction of these circuits into wireless telegraph practice. The examination of the question as to the priority of the different claimants to this improvement is fraught with considerable difficulty. Lodge, and Marconi in England, and Braun in Germany, have clearly established dates of publication by patent applications. While examining the question of priority, I shall also give a brief description of the apparatus of these several inventors, so far as pertains to the form of circuits used.

Sir Oliver Lodge's Apparatus. — On May 10, 1897, Professor Lodge filed a patent application in England for improvements in

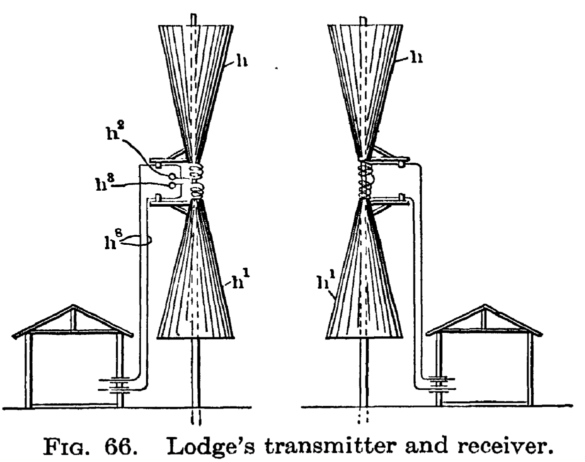

FIG. 66. Lodge's transmitter and receiver.

wireless telegraphy. The corresponding application in the United States was filed Feb. 1, 1898. What he claims to be the most promi-

charging into the antenna circuit, and if the coil k has a large inductance, as it seems to have from the fact that it is made of "fairly thin wire," this sending arrangement may be looked upon as a special and very imperfect form of the direct-coupled type of sending circuit of Fig. 65. It is imperfect in the use of the multiplicity of spark gaps, for if all the gaps except $h^{10}h^{11}$ had been closed, the coil k, which was put in as a charging bridge across the unnecessary gaps, could then have been omitted, and the apparatus would have been a very useful form of direct-coupled emitter.

While we are accustomed to the use of multiple gaps in replacement of a single gap, and while the multiple gap is in some constructions a distinct advantage over the single gap, still the introduction of one of the multiplicity of gaps directly into the antenna circuit

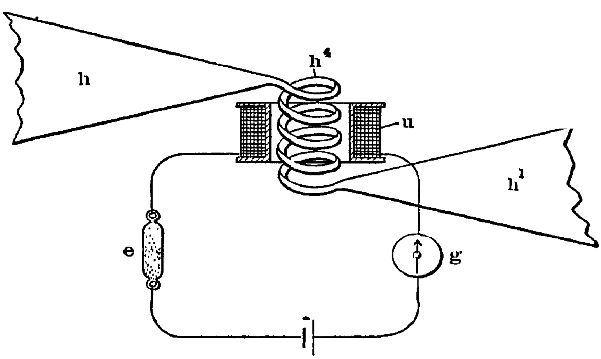

FIG. 68. Lodge's inductively coupled receiving transformer.

is certainly an annulment of the chief advantage accruing from the coupled circuits.

In the receiving apparatus Lodge shows the use of an oscillation transformer. Reference is made to Fig. 68. His conical capacity areas or their equivalent are connected to the primary coil h^4. About this a secondary coil u is placed, and is connected with the coherer e, a battery f, and the telegraphic receiving instrument g. The purpose of connecting the detector in a secondary circuit instead of directly in the antenna, is, according to the patentee, to "leave the resonator freer to vibrate electrically without disturbance from attached wires." This is an excellent reason, but the receiving apparatus, as shown in this diagram, which was taken from Lodge's patent specifications, has the fatal defect that no condenser is shown in the secondary circuit, and that the high-frequency oscillations have to go through the telegraph instrument. Hence, apart from the suggestion of the

inductance L added below the gap, for preserving approximate electrical symmetry and for tuning.

In addition to these various suggestions by Lodge in regard to the use of tuning coils and transformers in the circuits, and the maintenance by him of the possibilities of the ungrounded circuits, Professor Lodge, together with Messrs. Muirhead and Robinson, has also devised a new form of coherer. This is described in Chapter XVI.

The Coupled Circuits of Ferdinand Braun. — Let us return to the matter of the coupled circuits. In a German patent, No. 111,578, applied for October 14, 1898, Professor Ferdinand Braun of Strassburg in Germany describes "a

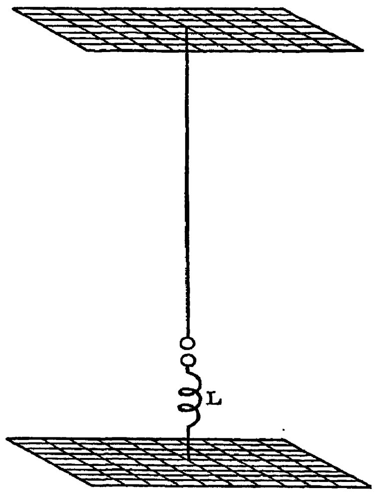

FIG. 70. Elevated conductor and ground of wire netting (Lodge).

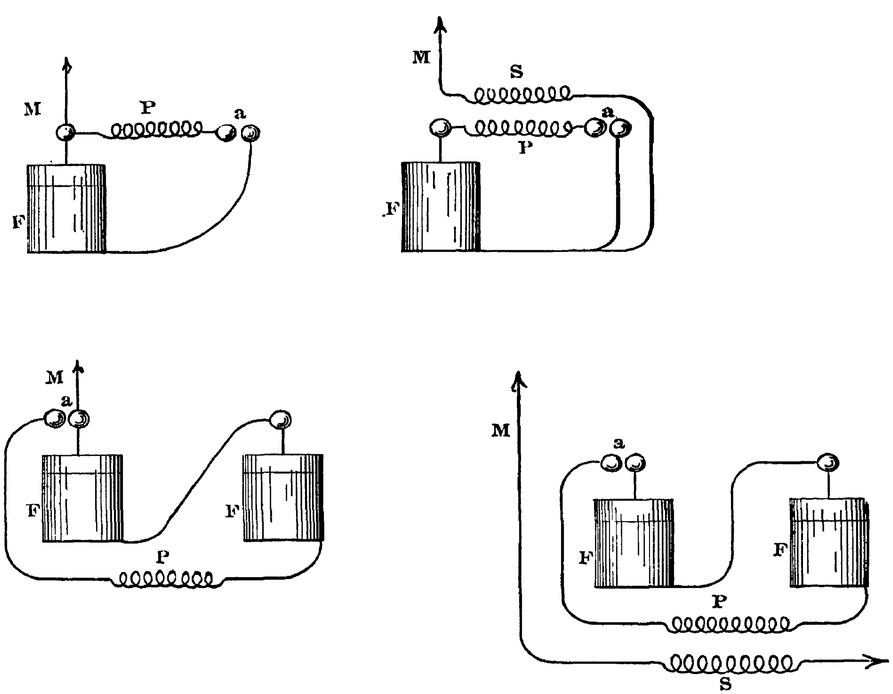

FIG. 71*a*, 71*b*, 71*c*, 71*d*. Professor Ferdinand Braun's methods of coupling a condenser circuit to an antenna.

patent, filed Feb. 6, 1899, does Professor Braun speak of the necessity of properly attuning the secondary circuit to the period of the condenser circuit, which is a prerequisite for attaining the high potential in the antenna circuit, and without this attuning of the secondary to the primary circuit, the large capacity of the primary condenser and the use of powerful sources of electricity would not give any advantage over the simple Marconi antenna.

The first mention by Braun of the required tuning, so far as I have been able to find, is in a publication of the 5th of March, 1901, in the *Physikalische Zeitschrift*, Vol. 2, p. 373, and in a book by Braun entitled *Drahtlose Telegraphie durch Wasser und Luft*, published in 1901.

In examining Braun's patent drawings one may wish to know whether the antenna circuit is to be grounded or otherwise balanced by a capacity at the other end of the secondary. Nothing is said on this subject in the German patent, but in the corresponding American patent he says, with reference to Fig. 71*d*, that "one end of the secondary coil of the transformer *S* is connected with the transmitting wire *M*, and the other end is shown prolonged and ending in an arrow to indicate that it may be prolonged by adding a suitable length of insulated wire or connected to some other capacity area." In his book of 1901 a corresponding prolongation or addition of capacity is indicated in his drawing of the direct coupled circuit, as is shown in Fig. 72.

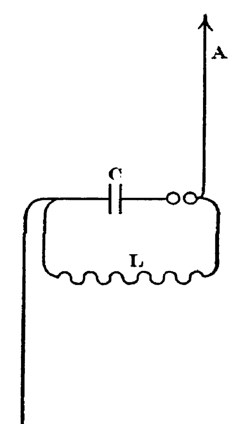

Fig. 72. Form of direct coupled transmitter devised by Ferdinand Braun.

There is nothing in these early patents of Professor Braun relating to coupled circuits at the receiving station. The coupled receiving circuits were undoubtedly invented by Marconi, and also his description of the inductively coupled sending station, though of published date a little later than that of Braun, is a much fuller and a more complete disclosure of the invention. The work of Marconi in developing the coupled circuits will now be discussed.

Marconi's Coupled Circuits. — Mr. Marconi, in an English patent applied for June 1, 1898, clearly sets forth the transformer arrangement for a *receiving station*. This is shown in Fig. 73, in which *A* leads to the antenna, and *E* to earth. The coils $J^1 J^2$,

of each other — that is to say, the electrical time periods of the four circuits are to be the same or octaves of each other."

The advantages of the coupled circuit at the sending station, according to Signor Marconi, arises in "the approximately closed circuit of the primary being a good conserver and the open circuit of the secondary being a good radiator of wave energy."

The variable inductance *g* in Fig. 74 placed in the antenna of the sending circuit and a corresponding coil at the receiving station were used to aid in this process of tuning.

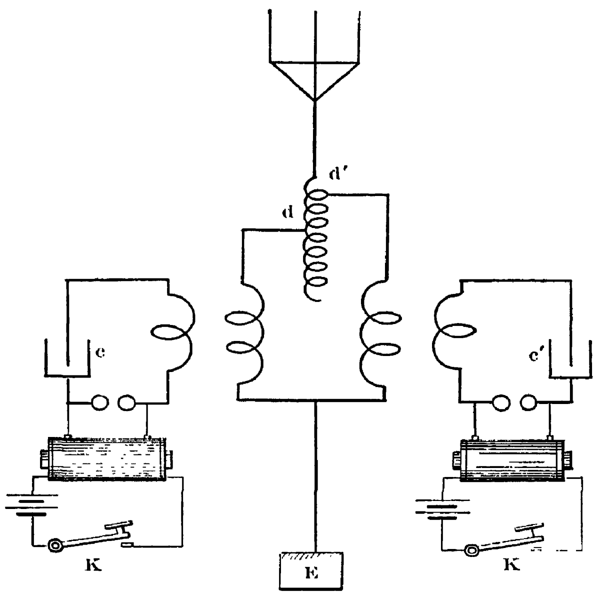

FIG. 75. Apparatus used by Marconi for sending two messages at once.

A sending and a receiving station devised by Mr. Marconi for sending or receiving two messages at once with the use of a single antenna are shown in Fig. 75 and Fig. 76. This was successfully employed and exhibited by Marconi in the autumn of 1900. Two operators at the two keys *K* and *K* of the sending station made the signals. The two condenser circuits having different values of capacity and self-inductance were independently charged, and discharged with different periods of oscillation. These two periods were both impressed on the antenna through circuits which by means of the antenna inductances *d* and *d′* were made to resonate with the respective condenser periods. At the receiving

supported by a kite. The detector employed in the transatlantic experiments was an instrument known as the "Italian Navy Coherer," and consisted of a globule of mercury between iron terminals in a glass tube. This form of detector is self-restoring, and with it a telephone receiver in series with a battery is used in the local circuit in the place of the ordinary telegraph relay.

In March, 1902, messages sent out from Poldhu were received by the Marconi apparatus on board the steamer *Philadelphia* when the steamer was 1550 miles (2400 kilometers) from the sending station. In December of the same year Marconi announced the transmission of three entire messages from Glace Bay, Nova Scotia, to Poldhu in England, a distance of 2300 miles.

On January 19, 1903, the powerful Marconi station at Wellfleet, Cape Cod, Massachusetts, transmitted to Poldhu, England, the following message from the President of the United States to the King of England:

"HIS MAJESTY, EDWARD VII,
London, England.

In taking advantage of the wonderful triumph of scientific research and ingenuity which has been achieved in perfecting a system of wireless telegraphy, I extend on behalf of the American people most cordial greetings and good wishes to you and to all the people of the British Empire.

THEODORE ROOSEVELT."

WELLFLEET, MASS.,
January 19, 1903.

This message, though intended to be relayed at Cape Race, was received, according to reports issued by the Marconi Company, direct at the Poldhu station in England.

If the electrostatic capacity per unit of length of the rods is uniform throughout both rods, which is approximately true, when the rods are not too short the potential of the conductor at any point of its length will be proportional to the charge, so that the shaded area representing a distribution of positive *charge* may also be looked upon as showing the distribution of positive *potential*, while the unshaded area represents negative potential. Thus, in the condition depicted in diagram (*a*), there is a uniform positive potential over

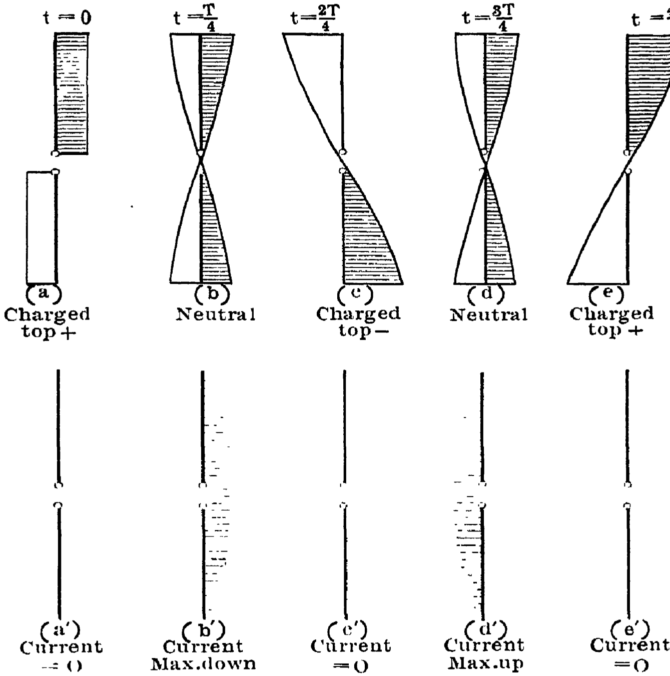

FIG. 77. Potential and current distribution.

the top rod, and a corresponding negative potential over the bottom rod. This is before the spark begins.

Suppose, now, the spark to start between the rods; the gap between the rods becomes conductive, and a current begins to flow between the rods. There is a flow of positive electricity from the top rod and a flow of negative electricity from the bottom rod. The electricity to flow first across the gap is that in the neighborhood of the spark gap, because it is there that the potential gradient is greatest. After a short time — one-fourth the period of a complete oscillation — the condition of the charge, and likewise the potential, of the rod

because any diminution of the current diminishes the surrounding magnetic field, and gives an electromotive force tending to preserve the current. The current thus continues to pile up a positive charge on the lower rod, in spite of the fact that this piled-up charge is exerting a restoring force.

Presently, however, this restoring force, which has gone on increasing, brings the current to a stop. Then when there is no current, there is no magnetic field, and the accumulated positive electricity on the lower rod starts the current upward. This reversal of the current occurs at a time $t = T/2$; and the condition of the charge and current is represented at (c) and (c'). The upward current continues to flow, and produces successively the conditions (d) and (d'), at $t = 3T/4$, and (e) and (e') at $t = T$.

In the last named state the upper rod is entirely positive, while the lower rod is entirely negative. This resembles the initial state of the rod, but is not identical with it, because the initial state was brought about by an extraneous slow charging source (Holtz machine or Ruhmkorff coil) instead of by the very rapid surging that is going on in the oscillator when it is oscillating with its own natural period.

From the condition of initial uniform distribution we have followed the charge and current, by rather large stages of a quarter of a period each, through a single oscillation. The charge on the conductor will continue to oscillate, going through the successive steps several times — the accumulation of electricity becoming less and less at each oscillation until the spark extinguishes.

Nodes and Loops of Potential and Current. — From the preceding discussion it is apparent that the two ends of the Hertz oscillator undergo maximum fluctuations of potential, and are, therefore, *loops of potential*. The middle of the conductor during the oscillation has no accumulation of charge on it; the potential of the middle, therefore, never rises above zero (after the start), and is a *node of potential*.

On the contrary, the *nodes of current* are at the ends of the oscillator, while a *loop of current* is at the middle of the oscillator.

EXPERIMENTS ON THE DISTRIBUTION OF CURRENT IN AN UNGROUNDED HERTZ OSCILLATOR

In the preceding dicussion there was given a theoretical examination of the nature of the potential and the current distribution occurring in a Hertz oscillator. I have recently made a simple

L, 30 cm. on a side, and having in series with it a variable condenser *C* and a high-frequency current-reading instrument at *I*. I shall now describe the instrument *I* and the condenser *C*.

Description of the Instrument. — The instrument at *I* as is shown in Fig. 80 consists of a disc of silver, suspended by a fine fiber of spun quartz so as to hang near a small coil of a few turns of wire, with which the disc made an angle of 45 degrees. The disc is at *M*, and the coil, which in this experiment consisted of five turns of wire wound on a vulcanite tube, is shown at *C*, Fig. 80. The two ends of the coil are connected to binding posts, by which the coil is put into the circuit. The front of the disc carries a small mirror, enabling the deflections of the disc to be measured by means of a telescope and scale such as is used with delicate galvanometers.

The mounting of the instrument is also shown in Fig. 80. The disc is suspended in the vertical vulcanite tube, which is mounted on leveling screws; the support of the coil is inserted in the side of the vertical tube, and is arranged to be moved in and out by a micrometer screw. This delicate motion of the coil in or out brings the coil nearer to or farther from the suspended silver disc so as to vary the sensitiveness of the instrument, to make it suitable for measuring small or large oscillating currents.

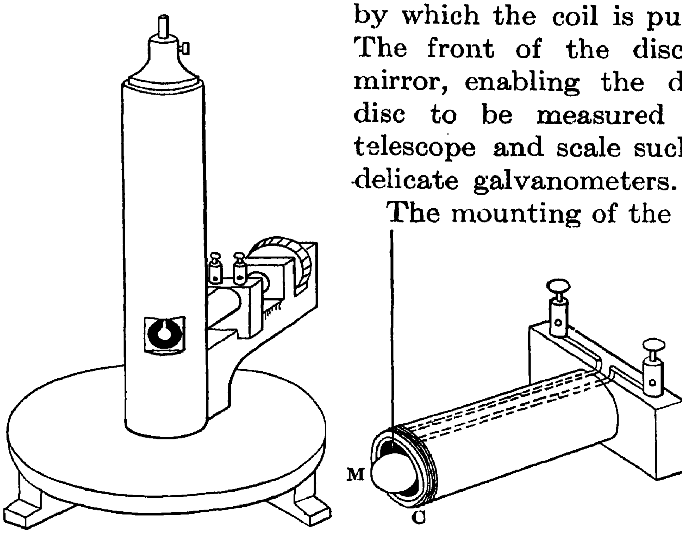

FIG. 80. High-frequency dynamometer. Mounting shown at left, suspension at right.

The action of the instrument, which we shall call a "high-frequency dynamometer," is as follows: oscillations in the coil induce oscillations in the disc. Between these two sets of oscillations there is a force which causes the disc to tend to set itself at right angles to the coil.[1] The deflections of the dynamometer are proportional to the square of the current through it.[2]

The principle of this instrument was independently discovered by Dr. Elihu Thomson and by Professor Fleming. The instrument was first shown

this character, with capacity somewhat larger than that of the condenser employed in these experiments, is shown in Fig. 81.

Large Current at Resonance. — Variations of the capacity of *C* varies the natural period of oscillation of the condenser circuit, and when this period is made equal to that of the Hertz oscillator *OGO*, a maximum deflection of the instrument *I* is obtained, under the action of the oscillation.

The resonant condenser circuit when calibrated in terms of wave length is a form of "wave meter." How this calibration is effected will be shown later.

Exploration of Current Distribution. — Since the wave meter in this form, on account of the instrument *I*, is not conveniently movable, it was necessary to move the oscillator in order to explore the distribution of current in the oscillator. The oscillator, with its exciting induction coil and storage battery, was moved lengthwise, keeping it always the same distance from the wave meter, by means of the vulcanite guides *DD* of Fig. 79. Readings of the dynamometer were taken for various positions of the oscillator with respect to the wave meter. This was equivalent to moving the wave meter along the oscillator, and the readings of the dynamometer were proportional to the square of the current in the wave meter, and therefore proportional to the square of the current at different points of the oscillator; because the induced current, keeping everything else the same, is proportional to the inducing current.

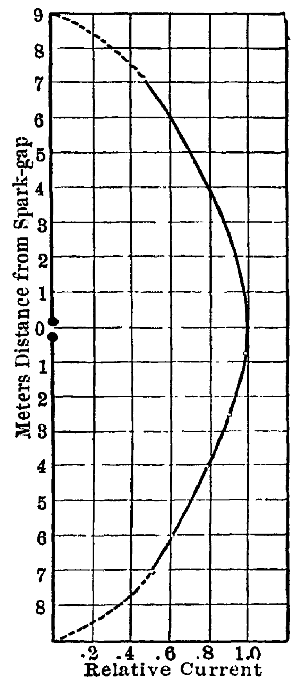

FIG. 82. Distribution of current along a Hertz oscillator, as determined by experiment.

The results obtained for the distribution of the current in the oscillator are plotted in Fig. 82. The curve of Fig. 82 shows that the current in the oscillator is greatest near the gap and falls off to zero at the ends of the oscillator in a manner not very different from that shown in the theoretical drawings of Fig. 77. There is a loop of current in the middle and a node at each end of the oscillator.

and we must therefore conclude that the ratio of λ/l for very short oscillators is greater than for the long oscillator.

We are primarily interested in the long oscillators, and in order to extend the experimental records to the case of longer oscillators than those studied by Conrad, I have made a series of measurements with the apparatus of Figs. 78, 79, 80.

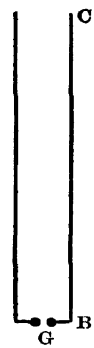

FIG. 83. Parallel-wire oscillator for calibrating wave-meter for short wave-lengths.

Calibration of the Wave Meter. — The wave meter was calibrated for various adjustments of the condenser C by setting it to resonance with various lengths of the two parallel wires of Fig. 83, as had been previously done by Drude. With the wave meter calibrated to read directly in wave lengths, the parallel calibrating wires were removed, and the Hertz oscillator, consisting of two oppositely extending wires of various lengths (1 mm. in diameter), was brought up near the wave meter, and the wave length produced by the oscillator was determined. The results obtained are given in the following table:

AUTHOR'S TABLE OF RESULTS FOR RELATION OF λ TO l

l Half length of oscillator in meters.	λ Wave length in meters.	$\frac{\lambda}{l}$
4.0	16.9	4.22
4.5	18.9	4.20
5.	21.2	4.23
5.5	23.2	4.22
6.	24.9	4.15
7.	29.5	4.21
8.	33.6	4.20
9.	38.7	4.23
10.	41.6	4.16
11.	46.1	4.22
12.	49.5	4.13
13.	53.9	4.14
14.	57.5	4.11
15.	63.0	4.19
	Average	4.19

The average of the results obtained by the author for the ratio of λ to l, namely, $\lambda/l = 4.19$, for wave lengths between 17 and 63 meters, is a little less than the corresponding ratio, 4.24, ob-

If the capacity attached were very large (e.g. the earth), the point of zero fluctuation of potential would again be brought near the instrument, because a large fluctuation of potential cannot occur in a very large capacity under the action of the currents with which we are concerned. We should, therefore, have the same current as when the conductor was made up of two parts symmetrical about the instrument.

In actual systems, the grounding may be imperfect. In that case the symmetrical image would give only approximately an equivalent system.

I have made some experiments to test this image theory of the action of the ground connection. The experiments consisted in comparing resonance curves taken with various forms of grounded circuits with the corresponding resonance curves taken with an image circuit in the place of the ground. Two of these experiments are here briefly described.

EXPERIMENTS TO TEST IMAGE THEORY OF THE GROUND

Experiment I. The Aerial Circuit and its Image Tuned by Variable Inductances. — In testing the image theory of the action of the ground at the receiving station the form of circuit shown in

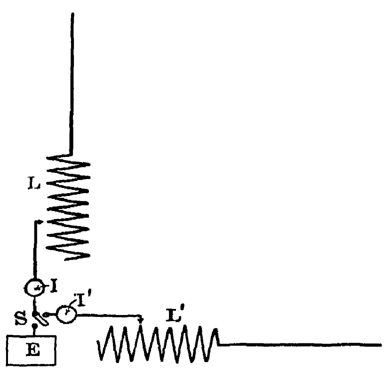

FIG. 84. Circuit employed in study of the image theory of the ground.

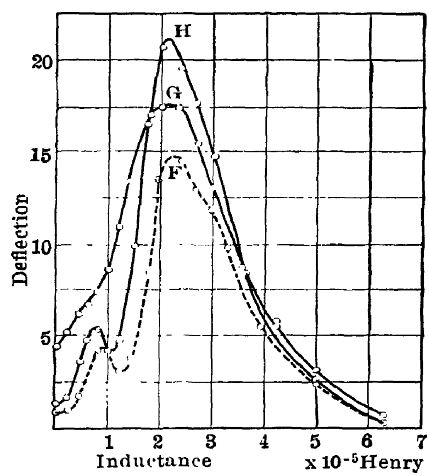

FIG. 85. Resonance curves in study of the image theory of the ground. Curve *H* was obtained with horizontal duplicate of antenna; curve *G*, with ground.

Fig. 84 was employed. The high-frequency dynamometer described on p. 113 was used for detecting and measuring the minute oscillating currents at the receiving station, and was placed at *I*

The curve F, with which we are not here concerned, was obtained with the duplicate antenna wound around the house of the receiving station.

Experiment II. Quarter-Wave Ground. — What was perhaps a more interesting experiment confirmatory of the image theory of the ground was made by replacing the ground by a horizontal wire of which the length could be varied. The relative amounts of energy received (deflections) for different lengths of the horizontal wire are shown in the curve A of Fig. 86. Resonance was obtained when this wire had the length of 38 meters, which was very close to one-fourth the wave length (153 meters). The ground gives the system the same period as an added quarter-wave wire gives the system. Curve B obtained with different conditions leads to the same results.

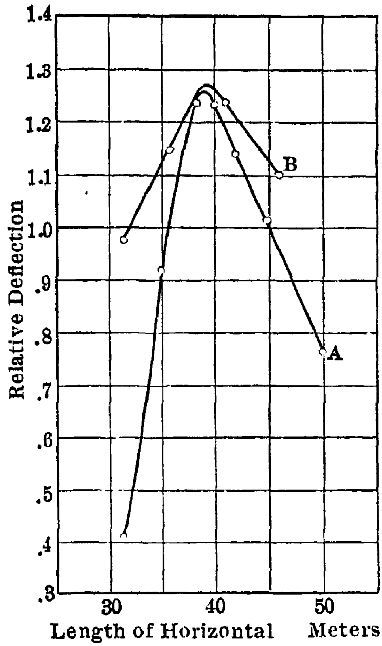

FIG. 86. Showing that the ground may be replaced by a quarter-wave wire.

Conclusion from the Experiments. — These experiments I and II show that the effect of the ground, so far as concerns the vibration in the antenna, is to introduce into the circuit at the ground a point of zero fluctuation of potential, — an effect that can also be obtained with an artificial ground consisting of a symmetrical duplicate of the aerial system or consisting of a horizontal wire not far from the earth and of length equal to one-quarter of the wave length to be received.

Professor Ferdinand Braun at a date earlier than that of my experiments has suggested the use of horizontal wire in replacement of the ground and also the use of a capacity consisting of a large cylindrical conductor in the place of the ground. He has not, however, so far as I know published any quantitative results on the subject.

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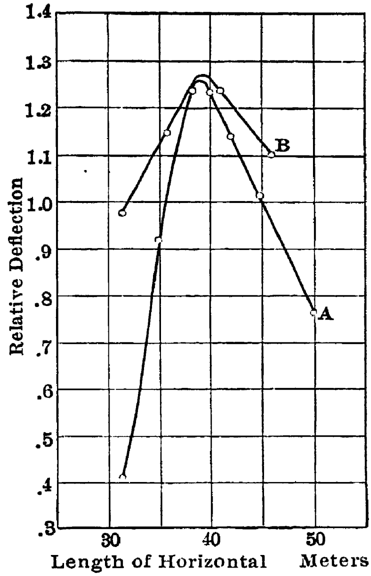

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pendicular to the direction of motion when the charge is brought up along the plane, and the work done is therefore zero. For further details in regard to work and potential see Appendix I.

Having shown that the plane P is everywhere at zero potential, let us next introduce the idea well established in treatises on electricity, that so long as we keep the potential of the plane P equal to zero the electric force in the region between A and the plane P is completely fixed, no matter what changes we may introduce below the plane. If, then, the lower half of the diagram is removed and the plane is in some other way kept at zero potential, the electric force between A and the plane will be the same as before; namely, that represented in Fig. 88, which is the upper half of

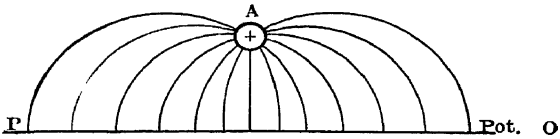

FIG. 88. Lines of electric force between a charged body A and an infinite conducting plane kept at zero potential.

Fig. 87. We may keep the plane at zero potential by grounding it so that it comes into coincidence with the surface of the earth; or the surface of the earth itself may take the place of the plane, provided the earth for a considerable area around the charged body A is a good conductor.

That is to say, if the earth's surface is a good conducting plane for a considerable extent, and a charged body A be placed above the surface of the earth, the field of electric force between A and the plane surface of the earth will be the same as the upper half of the field between A and a body B, which has a charge equal to A and opposite in sign, — B being at the distance below the plane that A is above it. This equal opposite charge symmetrically placed in regard to the plane is called *the electrical image of A* in the plane.

Similar Theory Applied to the Oscillator. — If we next consider the case of the electric oscillator, the field of electric force for the symmetrical oscillator, as we have seen in Chapter VIII, is roughly that represented in Fig. 89. The ideal, nonmaterial plane PP through the figure is at zero potential, so that the lower half of the diagram could be replaced by the surface of the earth, if it were plane and perfectly conductive, without disturbing the upper

are not visible from each other. We have here a simple view of the matter, obtained on the assumption that the earth is a perfect conductor.

The Earth not a Perfect Conductor. — The surface of the earth is, however, not everywhere a good conductor of electricity. The sea and moist soil are better conductors than dry stone. In some places the surface materials of the earth are in fact good insulators.

The attenuation of the electric wave is on this account very different over different parts of the surface of the earth, — conditioned on the fact that there is a greater or less penetration into the insulating portions and a greater or less absorption of energy at the poorly conducting portions. This subject has been submitted to a very remarkable mathematical treatment by Dr. Zenneck. The mathematical reader is referred to Dr. Zenneck's paper [1] or to Professor Fleming's [2] translation and "free paraphrase" of it, for a beautiful discussion of this interesting question. I shall attempt to give here a brief statement of some of Dr. Zenneck's results without attempting to present his reasoning. In doing this I wish to acknowledge the assistance afforded by Professor Fleming's excellent commentary on Zenneck's paper.

In order to simplify the matter, Dr. Zenneck at first considers only the case of a *plane electric wave* traveling without divergence over a flat surface. He is thus at first leaving out of account the spreading out of the wave and the consequent diminution of amplitude by mere distance; and he is also omitting the attenuation of the wave due to the curvature of the surface.

Instead of considering the earth to be a perfect conductor, as has usually been done before, Zenneck looks upon the boundary between the earth and the air as the boundary between two media of different conductivities and different dielectric constants; and he transforms Maxwell's equations so as to take account of the two media.

He arrives at the conclusion that where the earth is a good conductor (for example, *sea water*), the electric force (at the surface) is perpendicular to the surface. For waves of wave length 600 meters, which is the wave length used in most of the calculations, sea water acts as a good conductor, and the electric force at the surface of the sea is perpendicular to the surface, as is shown in

[1] J. Zenneck: Annalen der Physik, Vol. 23, 1907.

[2] Fleming: Engineering (London), June 4 and 11, 1909.

considering a radius drawn from the center of the ellipse to a particle moving around the ellipse with the frequency of the wave. The length and the direction of the radius so drawn would represent the changing magnitude and direction of the electric force. Such an electric wave, oscillating both in magnitude and direction is equivalent to two waves, one tending to produce vertical currents and the other tending to produce horizontal currents (the two effects being also out of phase with each other). The horizontal oscillating force induces currents in the earth's surface, and diminishes the energy of the progressing wave, so that in this case the distance to which signals can be sent is less than in the case of the good conductor.

In the case of *propagation over very dry soil,* which is not so good an insulator as the rock (r = 10,000 ohms per meter cube, k = 1 to 3) Zenneck finds the result represented in diagram (*c*), Fig. 91.

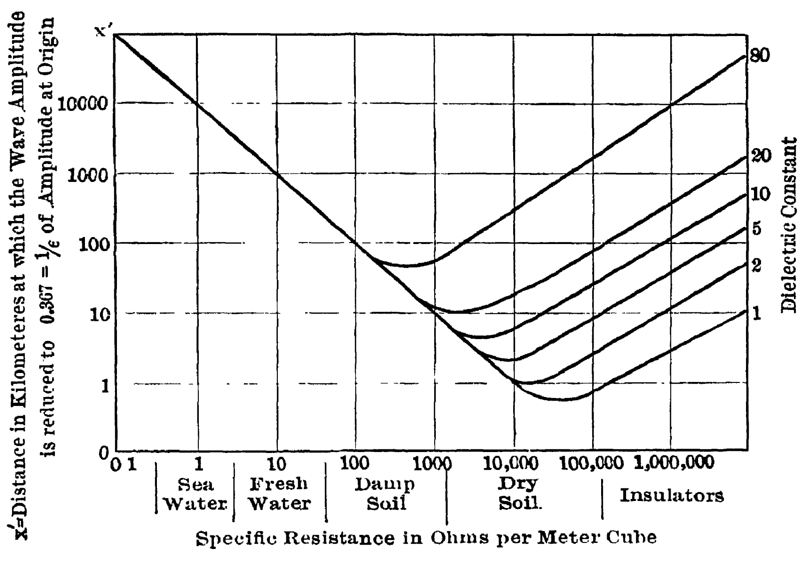

FIG. 93. Curves taken from Professor Fleming's commentary on Zenneck's theory, from the Electrician.

Although the conductivity in this case is between that of (*a*) and (*b*), the form of the ellipses is not intermediate between (*a*) and (*b*). The relation is not a simple one, involving resistance alone; because, in fact, a perfect conductor and a perfect insulator give in the region above the surface the same form of unabsorbed, vertical wave; and there is an intermediate case of conductivity and dielectric con-

space, and would not be constrained at all to follow the curvature of the surface.

From this it is clear that for the easy transmission of the electric waves between stations sufficiently separated to have a large portion *of the earth's curved surface between, what is required is a good conducting and not an insulating* expanse for the waves to travel over. In the succeeding sections we shall compare the distance of transmission over poor conductors with that over a good conducting expanse. To do this we must take into account the divergence of the waves with distance to see whether or not the absorption is important in any particular case.

Diminution of Amplitude by Divergence with Distance. — On account of the divergence of the waves from the sending station, the amplitude of the electric force in the wave is approximately inversely proportional to the distance from the oscillator, provided there is no absorption and provided the distance is not too small. This has been shown theoretically to be true in the case of the propagation of the waves in free space. This law has also been approximately verified for wireless telegraph waves traveling over sea water for distances up to 60 miles, in a very beautiful set of experiments performed on the Irish Channel by Messrs. W. Duddell and J. E. Taylor.[1]

Messrs. Duddell and Taylor's experiments consisted in receiving and measuring the current set up in the antenna of a shore station by electric waves sent out from the British telegraph repair ship *Monarch*, while the ship was at various distances from the receiving station. The very minute currents received were measured by Duddell's thermogalvanometer, of which the following is a brief description:

The thermogalvanometer invented by Mr. W. Duddell[2] is in principle the Radiomicrometer of Professor C. V. Boys, with a modification required to adapt it to measuring oscillatory electric currents instead of heat radiation, for which Boys' instrument was designed. A diagram of the essential parts of the instrument is shown in Fig. 94. Between the poles NS of a strong permanent magnet is hung a small loop of one turn of wire L, by means of a very fine quartz fiber F. The loop is closed below by a thermal junction of bismuth Bi and antimony Sb. Heat applied in any

[1] Duddell and Taylor: Journal of the Institution of Electrical Engineers, Vol. 35, pp. 321–352, 1905.

[2] W. Duddell: Phil. Mag., Vol. 8, p. 91, 1904.

Monarch. In these curves the product of received current times distance is plotted against the distance. If this product were a constant, the curves should each be a straight line parallel to the horizontal axis. It is seen that between 16 and 60 miles each of the three curves is approximately horizontal. Messrs. Duddell and Taylor's measurements will therefore be seen to show that the received current from a given constant sending station is

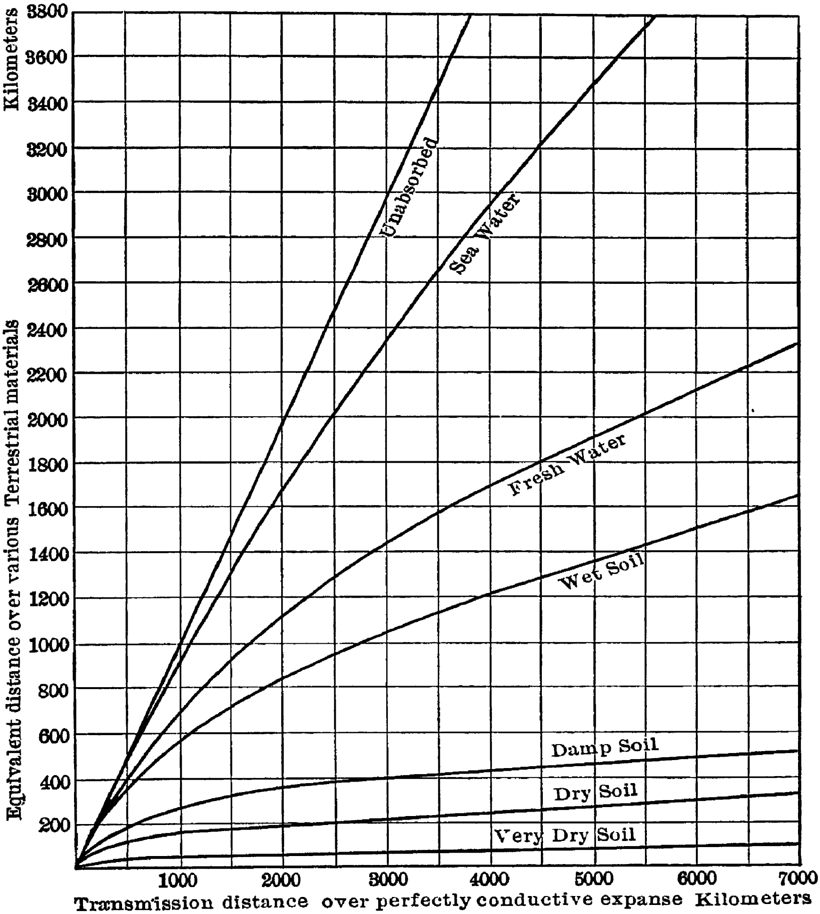

FIG. 96. Comparison of transmission distances.

somewhat nearly inversely proportional to the distance. In view of the great difficulty of keeping the conditions at the sending station constant throughout each of the experiments, and in view of the difficulty of measuring the small currents received, Messrs. Duddell and Taylor deserve much praise for this laborious and

kilometers over a perfectly conductive expanse could be read at a distance of 2360 kilometers over the sea; 1450 kilometers over fresh water or a rain-soaked soil; 400 kilometers over damp soil, and only 70 kilometers over some kinds of very dry soil. Although exact quantitative experiments are lacking in regard to the equivalence of these various distances in a practical case, yet these figures do not seem to be very different from the reports of wireless telegraph engineers as to the comparative ease of attaining great distances over sea and over various kinds of land.[1]

A deduction of the numerical results shown in the above table by straightforward reasoning from Maxwell's theory of electric waves, and the agreement of these results with the facts of experience, ought to be sufficient to satisfy us that we are dealing with true Maxwellian electric waves and not with some new kind of electrical manifestation, as some writers have occasionally intimated.

Absorption Conditioned on Wave Lengths. — In discussing Zenneck's results we have confined our attention to a wave length of 600 meters. Zenneck has, however, shown how to modify his formulas in order to apply them to other wave lengths; and Professor Fleming has carried the calculations through for several other wave lengths, and draws the following conclusions:

"1. In the case of transmission over sea, the absorption for waves of 300 meters wave length is not very large; but, nevertheless, increasing the wave length to 3000 meters is an advantage.

2. In transmission over land the absorption of waves 300 meters long is very sensible, and increasing the wave length to 3000 meters produces a very beneficial effect.

3. In the case of extremely dry soil the terrestrial absorption is very large, and increasing the wave length from 300 meters to 3000 meters produces no marked improvement."

Effect of Bodies of Water below the Earth's Surface. — For information on this subject the mathematical reader is referred to an article by Dr. F. Hack, *Annalen der Physik*, Vol. 27, p. 43, 1908.

The Effect of Light and Darkness on Transmission. — Another important subject connected with the long distance transmission of wireless telegraph signals is the effect of light and darkness on transmission distance. In experiments conducted between

[1] See on this subject, Capt. H. B. Jackson, R.N., F.R.S., "On Some Phenomena affecting the Transmission of Electric Waves over the Surface of Sea and Earth," Proc. Roy. Soc. London, 1902, Vol. 70, p. 254. Also Fleming, The Principles of Elec. Wave Telegraphy, 1906, p. 606.

waves, so that these high-frequency currents are given a unidirectional character and may be measured on a galvanometer by reading its deflections, or they may also be measured on a telephone receiver by determining what shunt is necessary about the telephone to reduce its sound to inaudibility. The telephone method is the more convenient and this was usually employed by Pickard, who, however, reduced his observations to galvanometer readings

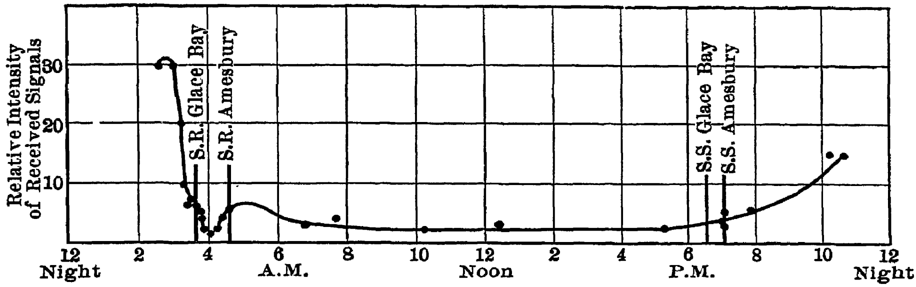

FIG. 97. Observations taken by Mr. Pickard on the relative intensity of signals received at different hours of day and night.

by calibration and by control experiments. The *relative intensities of received signals*, plotted in the diagrams, are the rectified currents produced by the electric waves in terms of that rectified current which will produce just audible sounds in the telephone.

We have not yet had a discussion of these crystal rectifiers as used to detect or measure electric waves, but it should be said in passing that on account of the characteristics of these detectors the relative intensities here plotted are not proportional to the energy or to the alternating current generated by the received signals. We must therefore look upon the intensity values of Mr. Pickard's curves as conditioned by the form of detector used. Since, however, the detector employed was one of high sensitiveness and one much used in commercial wireless telegraphy, these curves obtained under actual working conditions are highly instructive. As a precaution against changes that might occur in the detector, Mr. Pickard repeatedly tested the detector by throwing it into a circuit containing a constant small alternating electromotive force and a galvanometer, and when necessary the detector was readjusted so as to give a fixed rectified current under the fixed e.m.f.

By a reference to the curves of Fig. 97 we see that for the particular crystal detector, used with a 2000-ohm telephone receiver as in actual practice, there was obtained in the telephone receiver about 30 times as much current near midnight as during the daytime.

of day and night transmission of electric waves were first observed, the theory was at once advanced that the effect was due to the action of the daylight in rendering the air conductive for electricity. We have noticed in Chapter II that light, especially ultraviolet light, is one of those agencies that ionizes the air by breaking it up into charged positive and negative particles, and that air so ionized will conduct electricity in a manner known as convection; that is, if the ionized air is brought between two plates which are charged to different potential, the positively charged particles in the ionized air will be driven from the plate of higher potential to the plate of lower potential, while the negatively charged particles will be driven in the opposite direction. This motion of the charged particles constitutes an electric current flowing between the plates.

Inadequacy of Explanation Based on Conductivity of Air Near the Surface of the Earth. — This suggests two ways in which the effect of the light would act to decrease the distance of transmission by daylight, assuming that the air near the earth is more conductive in the daytime than at night.

(1) The conductivity of the air in the daytime in the neighborhood of the sending antenna would cause the charge to leak off the antenna so that it would not be charged to so high a potential and would therefore not produce so large an oscillating current as at night.

(2) The air in the interval between the sending and the receiving station, being more conductive in the daytime, would absorb more of the energy of the waves than at night.

Both of these explanations, based on the conduction of the air near the earth, seem entirely inadequate to explain the phenomenon. The first explanation is untenable because the effects of the daylight do not manifest themselves when the stations are separated by short distances, and can, therefore, not be localized at the sending station. As to the effect of absorption, if we take the average experimentally determined value for the conductivity of the air near the surface of the earth as 2×10^{-25} electromagnetic units for a centimeter cube of air,[1] and substitute this value in the formula [2]

$$A = A_0 e^{-\xi x},$$

where for small conductivity

$$\xi = 2 \pi \sigma \times 3 \times 10^{10};$$

[1] This value is taken, following Zenneck, from Gerdien, Physikalische Zeitschrift, Vol. 6, p. 647, 1905.

[2] This formula is derived in Boltzmann's *Vorlesungen ueber Maxwells Theorie*, § 96 (Leipzig, 1891).

regions of the atmosphere than at the surface of the earth, because the chief ionizing rays of light are those of very short wave length (the ultraviolet), and these short waves of light are strongly absorbed by the air, and therefore do not penetrate to a very great depth in the earth's atmosphere. The stratum of upper atmosphere, rendered conductive by the sunlight, may serve to some extent as a reflector of the electric waves so as to assist in confining the waves to the surface of the earth. If this effect were appreciable, the waves would be more strongly confined to the surface of the earth in the daytime than in the night, and transmission would be easier in the daytime than at night, except for a possible interference between the direct and the reflected wave. This interference, if it should exist, would intensify waves of some wave lengths and partially annul waves of a different wave length, so that by changing the wave length through a range corresponding to a half period it ought to be possible to turn the interference to advantage. No such effects have been found, and the increase of the conductivity of the upper air by ionization in daylight when looked upon as a reflector does not act in the proper direction to be the determining factor in explaining the inequality of transmission of electric waves by day and by night. Professor A. E. Kennelly has called my attention to the fact, however, that there may exist in the upper strata, as we pass upward, a gradual change from insulating to good conducting strata, which, coupled with irregularly distributed conducting areas, might result in a general deflection upward of the waves, and a consequent loss of received energy, and that this effect might be greater in daylight than at night. This theory has not yet been given exact mathematical expression, so that up to the present we seem not to have found an adequate explanation of the difficulties of daytime transmission in comparison with night transmission of electric waves to great distances. The question is one of great importance from a theoretical standpoint, and if the discovery of the explanation of the phenomenon should bring with it the discovery of a means for bringing the distance of communication by daytime up to that by night, it would remove a very exasperating limitation to electric wave telegraphy.

Experiments with the use of very long electric waves are under way by the National Electric Signaling Company and by the Marconi Company, and it is reported that some approach toward uniformity of day and night transmission has been made.

of a natural period of vibration. The following table (Table II) taken from Dr. Austin's paper gives the number of volts required to produce just audible sounds in the pair of telephone receivers under the application of sinusoidal electromotive forces of various numbers of complete cycles per second.

TABLE II.

VOLT SENSITIVENESS OF A PAIR OF SCHMIDT-WILKES 800-OHM TELEPHONES.

No. of cycles per second.	Volts to produce audible sound.
60	620 millionths of a volt.
120	290 " " "
180	170 " " "
300	60 " " "
420	17 " " "
540	8 " " "
660	3 " " "
780	1.1 " " "
900	0.6 " " "

Sensitiveness of Galvanometers. — A very sensitive galvanometer of ordinary construction and of about 1000-ohms resistance will give a visible deflection with less than one ten-millionth of a volt, but such an instrument has too slow a period (ten seconds) to use in indicating wireless telegraph messages. In 1903 Professor Einthoven [1] designed a new form of galvanometer that has a very rapid period and at the same time a high sensitiveness. Einthoven's instrument consists of a very fine silvered or platinized quartz fiber hung between the poles of a strong magnet. The current to be measured is sent through the silver or the platinum coating on the fiber, and the fiber tends to move out of the magnetic field. The deflections of this fiber may be observed with a microscope, or may be photographed on a rotating drum carrying a photographic film. The direction of the deflection of this galvanometer, like that of the ordinary galvanometers, reverses with reversal of the current. In one one-hundredth of a second Einthoven's instrument will give a deflection sufficiently large to be registered on the photographic plate, under application of an e.m.f. of one ten-thousandth of a volt. Used in connection with a suitable

[1] Annalen der Physik, Vol. 12, p. 1059, 1903.

CLASSIFICATION OF DETECTORS

We shall describe the detectors under the following more or less arbitrary titles:

Coherers.
Magnetic Detectors.
Thermal Detectors.
Crystal Rectifiers.
Electrolytic Detectors.
Vacuum Detectors.

In illustrating the manner of introducing these various detectors into the receiving system a diagram of only a simple form of receiving circuit will be exhibited with the descriptions. It is to be understood, however, that all the detectors can also be used in various forms of direct and inductively connected circuits as well as in the simple circuits.

COHERERS

As coherers, we shall include only those detectors which employ a loose contact and require to be shaken, tapped, or otherwise moved to restore the contact to its sensitive condition after the receipt of a signal. We have already described the filings-tube coherer of Branly and Marconi. A great many modifications of this instrument have been made, including the use of a single contact or a few contacts in series or parallel, between metallic balls or points, to take the place of the filings. Also a great many variations in the method of decohering the contacts have been made. These will not be described here.

These various forms of coherer have their importance in the fact that, on the receipt of electric waves, a sufficiently large current is started in the local circuit to operate a relay, ring a bell, or give other form of alarm that can be heard at a distance from the operator's desk. Also the current permitted to flow in the local circuit of the coherers during the receipt of electric waves is sufficiently large to start machinery and control a mechanism (for example, a torpedo or dirigible craft) at a distance. This kind of result is not easily attained with the other form of detectors listed above, which do not permit of the use of sufficiently large currents in the local circuit to sound an alarm or start electrical machinery.

This is evident from the fact that in some cases the metallic particles (e.g., iron or steel) are artificially prepared by oxidizing them in order to make of them a good coherer. The poorly conductive film may also be present in some cases in the form of a sulphide of the metal. On account of the readiness with which many metals (called the "baser metals") enter into combination with the oxygen or sulphur dioxide of the air, a thin film of oxide or sulphide is always present on the surface of most of the baser metals, unless special care is taken to remove it.

Apart, however, from the existence of such films of foreign matter at the contact, it seems not impossible that the high resistance before the arrival of the waves may be a property of the surfaces of even pure metals when these surfaces touch only very lightly.

If we assume the presence of the poorly conductive film at the contacts of the coherer, we may suppose that, on the arrival of the electric waves, the poorly conductive film is removed by the heat developed by the oscillatory currents. This starts the local current, which, developing further heat, still further improves the contact and permits the passage of further current. Instead of heat being the chief agency in removing the oxide or other poorly conductive film, or in bringing together the loose contacts, it may be that this is done by the electric attraction between the filings, which before the current starts will be charged with opposite signs of electricity, and which under the added e.m.f. produced by the electric oscillations may attract each other strongly enough to pull the contacts together.

We shall learn more about the electrical properties of high resistance contacts when we come to the study of *crystal rectifiers*. It is therefore proposed to omit further discussion of the specific action of the coherers, because of the more general character of the information to be presented later.

In the meanwhile some of the other detectors which do not depend on the properties of a loose contact are discussed.

MAGNETIC DETECTORS

Rutherford's Magnetic Detector. — In 1895 and 1896 Professor E. Rutherford[1] discovered a sensitive method of detecting electric waves by causing the electric oscillations set up by the

[1] E. Rutherford, "A Magnetic Detector of Electrical Waves and Some of Its Applications." Phil. Trans. Roy. Soc. London, 1897, Vol. 189, A., p.1; also Proc. Roy. Soc. London, 1896, Vol. 60, p. 184.

band where it approaches and leaves the coils. These magnets induce magnetic *poles* in the moving band. One of these induced poles, say the South pole, is within the coils, and the two other

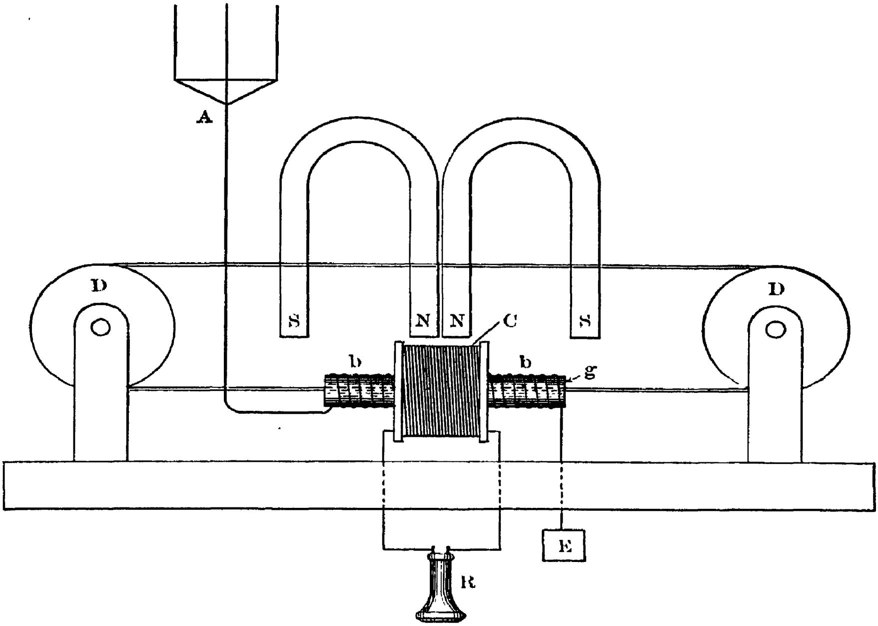

FIG. 100. Marconi magnetic detector.

consequent poles (North poles in our illustration) are near the point where the band enters and leaves the coils.

General Facts in Regard to the Explanation of the Action of the Marconi Magnetic Detector. — If we confine our attention to a point on the moving band, it is seen that, as the band moves forward, this point becomes a North pole outside the coils, changes to a South pole within the coils, and becomes again a North pole after issuing from the coils. There is, however, within the coils, *a steady state of magnetization*, for although the band is in motion, every particle of the band, as it passes a particular point within the coils, comes to a particular state of magnetization, so that the magnetic condition is fixed with respect to the magnetizing magnets. This gives a steady state of magnetization within the coils and produces no inductive effect in the form of currents in the telephone circuit.

If now a train of electric oscillations passes through the oscillation coil *b*, the magnetization of the part of the band within the

to discover just what is the effect produced on the magnetization of the bundle of iron wires by the oscillations within the coil surrounding the bundle. A steady current in the coil would magnetize the iron wires of the bundle. An oscillatory current, according to the experiments of C. Maurain, [1] *produces a suppression of hysteresis in the iron.*

In explanation of the term "hysteresis," reference is made to Fig. 101, in which *magnetizing force* is plotted horizontally and the *magnetization* produced by it is plotted vertically. This curve represents the *hysteresis* in a specimen of hard-drawn iron wire such as is used in the magnetic detectors. If we start with the magnetizing force equal zero, and increase it to OL, the magnetization follows the curve OA. If now we reduce the magnetizing force gradually to zero, the magnetization follows the curve AC. That is, the state of magnetization produced by the magnetizing force when it is decreasing is not the same as the state of magnetization produced by the force when it is increasing, and after the force is removed, some magnetization represented by OC is left in the specimen. In order to reduce this magnetization to zero, it is necessary to apply a reversed magnetizing force OD. If we go on increasing the reversed magnetizing force to OM, the magnetization follows the branch DE of the curve. On decreasing and again reversing the force, the magnetization traces out the branch $EFGA$. The complete diagram is called a *hysteresis cycle.*

Hysteresis is the property of iron, steel and other magnetizable metals characterized by the fact that the change in magnetization due to the application of a magnetizing force depends on the previous state of magnetization of the specimen. The state of magnetization assumed by a specimen when the magnetizing force is gradually removed is not the same as the state of magnetization assumed by the specimen when the force is gradually applied. The magnetization produced by a given magnetizing force is not completely annulled by withdrawing the magnetizing force. The hysteresis effect is small in very soft iron, is increased by hardening the iron, and is very great in glass-hard steel.

According to the experiments of C. Maurain, which we are now discussing in their application to the magnetic detector, the superposition of a sufficiently strong oscillatory magnetizing force upon a slowly varying magnetizing force causes a suppression of the hysteresis in the specimen. If the oscillatory force is weak, the

[1] C. Maurain, Comptes Rendus, Vol. 137, p. 914–916, 1903.

South poles and negative under the North poles; and following our usual method of plotting, the magnetizing force can be represented approximately by the *dotted wavy curve H* of Fig. 103. Now if we suppose the band to be moving in the direction of the arrows, the North magnetization under the first South pole will not follow the curve of force, but will *persist*, and follow approximately the continuous curve B. If now oscillations produced by the electric waves are allowed to flow around the oscillation coil, the hysteresis in the band is suppressed, so that the curve of magnetization B falls back into the position B', which is nearer the curve of magnetizing force H of Fig. 103. This change from the condition B to B^1 is equivalent to a motion toward the left of the magnetic distribution in the coil, and therefore induces a current in the coil containing the telephone in circuit. When the waves cease, the state of magnetization returns to that represented by the curve B. We have thus with each train of waves a back and forth shift of magnetization of the band, and consequently a to and fro motion of the telephone diaphragm.

While this description of the process seems a very reasonable explanation of the action of the detector, yet, for the benefit of those readers who may wish a little more insight into the processes occurring in iron or steel submitted to an oscillatory field, I beg leave to present a brief account of some experiments by E. Madelung, in which he made direct observations of the effect of electric oscillation on the magnetization of iron and steel.

Experiments of E. Madelung. — A very comprehensive and beautiful series of experiments *On Magnetization by Rapid Oscillations, and on the Operation of the Rutherford-Marconi Magnetic Detector* has been made by E. Madelung, and described in his Göttingen Dissertation.[1]

By means of a very ingeniously devised application of Braun's cathode tube, Madelung was able to obtain on a fluorescent screen the hysteresis cycle produced by a slowly varying magnetic force, and to obtain also the effect produced on this hysteresis cycle by superposing the rapidly oscillating magnetic force produced by sending a condenser discharge through the magnetizing coils.

Reference is made to Fig. 104. I. With a slowly varying magnetizing force the hysteresis cycle *EAKFGE* was described. II. Upon slowly applying and withdrawing a magnetizing force

[1] E. Madelung: Drude's Annalen, 1905, Vol. 17, p. 861.

A suppression of hysteresis would attain the same end results, but instead of being contented with calling the effect "suppression of hysteresis," which is a purely negative account of the phenomenon, Madelung, by his delineation of the spiral course taken by the magnetization during the application of the oscillating magnetic force, has given us a very distinct picture of the active processes occurring in the specimen. He has shown that the magnetic state of the iron has been violently agitated by the oscillating magnetic force, and in this way the sluggishness of the specimen in following the slowly changing magnetic force has been overcome.

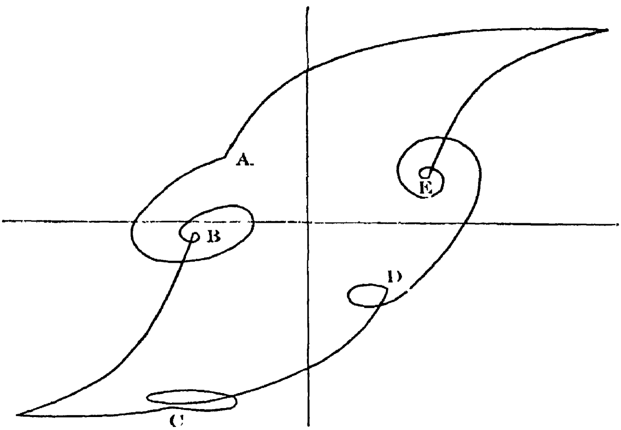

FIG. 105. High frequency oscillations superposed on different parts of cycle (Madelung).

Applying this process to our Fig. 103, we must think of the curve B as going through a set of vibratory tremors back and forth horizontally as it settles down toward the curve H. These tremors are of too high frequency to act on the telephone, which therefore responds only to the general displacement of the magnetization from the curve B toward the curve H.

Sensitiveness of the Magnetic Detectors. — The magnetic detectors are more sensitive than the coherer, but seem to be less sensitive than the electrolytic detector and some of the solid contact detectors (the crystal detectors).

THERMAL DETECTORS

There are two general classes of detectors in which the heat developed by the electric waves is made to manifest itself at the receiving station. In one of these classes, including the *bolometer*

this fine platinum wire, which may be as small as one or two ten-thousandths of an inch in diameter. In the finished instrument this fine loop of wire is inclosed in a glass or metal bulb, as shown in Fig. 106. The method of using the detector is shown in Fig. 107, which contains the detector *D* in series with the antenna *A* and ground *G* of a receiving station. In the local circuit about the detector is a battery *B* and a telephone receiver *T*. Oscillations in the antenna circuit passing through the detector heat the fine loop of wire. This changes the resistance of the little loop, and consequently modifies the current in the local circuit, and produces a sound in the telephone receiver. When the waves cease the little loop rapidly cools, restoring the current to its original value. The adaptability of the instrument to the receipt of signals is due to the very small heat capacity of the fine wire, by reason of which it heats and cools with sufficient rapidity to respond with the train-frequency of waves. The difficulty with the use of this instrument arises in its liability to be burned out when the signals become too strong.

In sensitiveness the barretter falls far below the sensitiveness of the electrolytic and crystal detectors to be described later, and its use, except for the purposes of laboratory measurements, has been practically discontinued.

Thermoelectric Detectors. — We have already described two thermoelectric detectors: Klemenčič's thermal junction (Chapter IX) and Duddell's thermogalvanometer (Chapter XV). These instruments change the energy of the electric waves into heat localized in a small amount of metal. The heat developed, in the case of Klemenčič's thermal junction, is developed at the thermal junction itself; while in Duddell's instrument the heat developed in the "heater" is conveyed by radiation and convection to the thermal junction. The heating of the thermal junction produces an electromotive force, which gives rise to a unidirectional electric current in the local circuit and produces a galvanometer deflection. We have in these instruments, first, a change of the energy of the electric oscillation into heat, and then a change of this heat energy again into electric energy. The instruments of Klemenčič and Duddell, though very useful for the purposes of measurements, are not sufficiently rapid or sufficiently sensitive for use in the reception of actual messages.

It has been found, however, that a high resistance contact between a common metal and certain crystalline substances, or

CHAPTER XVII

ON DETECTORS (*Continued*).—CRYSTAL RECTIFIERS

We come now to a very sensitive and interesting class of detectors for receiving the signals of wireless telegraphy and wireless telephony. These are the detectors consisting of a self-restoring high-resistance contact between solid bodies, and since one of the bodies is usually crystalline in character, I have given to this class of detectors the name *Crystal Rectifiers*.

The crystal rectifiers are self-restoring, and are usually employed with a telephone receiver; but a capillary electrometer or galvanometer can be used in the place of the telephone receiver. Many of the detectors of this type will give a very strong response *without a battery in the local circuit*, but most of them require the battery of small e.m.f. for the best sensitiveness.

Fig. 108 shows the connections for use of a self-restoring detector with a battery B in the local circuit. Fig. 109 shows the

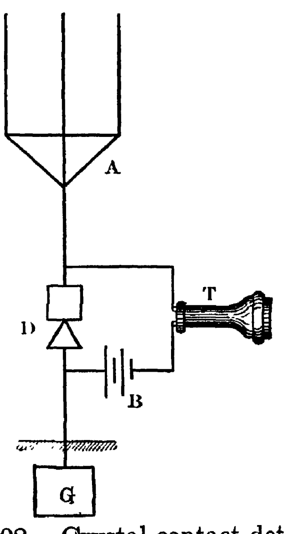

Fig. 108. Crystal contact detector with battery in local circuit.

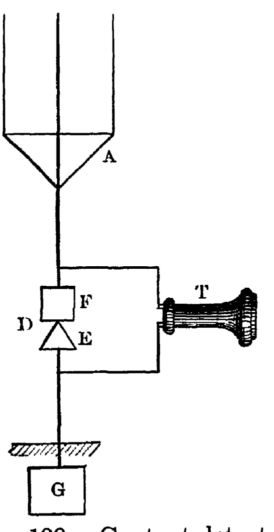

Fig. 109. Contact detector without battery.

detector without a battery. The detector D is shown attached to the antenna and ground in a very simple form of receiving circuit.

Mr. Fahie's History.[1] In this diagram, C is a carbon pencil touching a steel needle N; S is a brass spring by which the pressure of the contact can be regulated. The adjustment of the spring is regulated by means of the disc D.

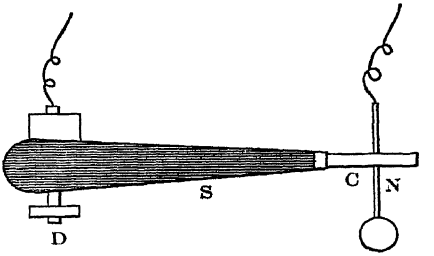

FIG. 110. Hughes's microphonic steel-carbon detector.

Professor Hughes used the microphone with or without a battery in the local circuit; and when the battery was omitted, he attributed the sound in the telephone to the thermoelectromotive force developed at the carbon-steel junction. The detector was more sensitive with a battery in the local circuit than without it.

Various modifications of this microphonic detector of Hughes have been employed in practical wireless telegraphy. One modification, which had a considerable application a few years ago,

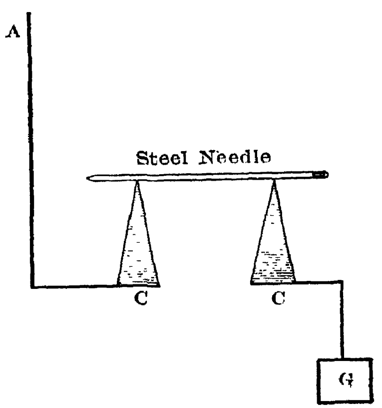

FIG. 111. Steel-carbon detector.

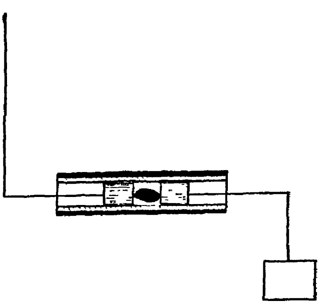

FIG. 112. Detector of carbon granule between metallic plugs.

is obtained by placing a steel needle across two blocks of carbon, as shown in Fig. 111. Another is made by placing a granule of carbon between metallic plugs in a tube, as shown in Fig. 112.

The microphone is more sensitive than the filings coherers. It is, however, somewhat troublesome on account of sensitiveness to mechanical vibrations and on account of liability to cohere under strong signals, and it is surpassed in sensitiveness to electric

[1] Fahie, History of Wireless Telegraphy, 1902, Dodd, Mead & Co.

Pickard's Crystal Detectors. — Mr. Greenleaf W. Pickard has been very prolific in the discovery of materials of a crystalline character that can be used as a member of contact detectors. Among the substances used and patented by him in this connection are silicon,[1] zincite,[2] chalcopyrite,[3] bornite and molybdenite.[4]

The mounting of Mr. Pickard's silicon detector, which is representative of a favorable method of constructing the detectors of this class, is shown in Fig. 113. A rod of brass *A* is pressed down by a spring *S* into contact with a mass of polished silicon *B*,

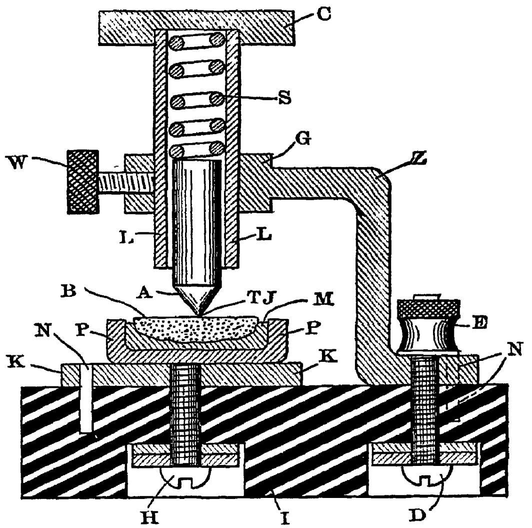

FIG. 113. Pickard's silicon detector.

embedded in an easily fusible solder of Wood's metal, *M*. The solder in which the silicon is embedded is contained in a metallic cup *P*, which rests upon a metallic plate *K*. Connection to the rod *A* is made by means of the binding post *E*. Connection to

[1] G. W. Pickard: Electrical World, Vol. 48, p. 1003, 1906; U. S. Patent, No. 836,531, filed Aug. 30, 1906, issued Nov. 20, 1906; U. S. Patent, No. 888,191, filed Nov. 9, 1907, issued May 19, 1908.

[2] G. W. Pickard: U. S. Patent, No. 886,154, filed Sept. 30, 1907, issued April 28, 1908.

[3] G. W. Pickard: U. S. Patent, No. 912,726, filed Oct. 15, 1908, issued Feb. 16, 1909.

[4] G. W. Pickard: U. S. Patent, No. 904,222, filed Mch. 11, 1907, issued Nov. 17, 1908.

(1) In determining what currents would flow through the detector under a given steady electromotive force;

(2) In an oscillographic study of the instantaneous values of the current through the detector under the action of an alternating e.m.f.;

(3) In measuring the thermoelectric properties of some of the specimens and comparing the thermoelectromotive force with the rectified current.

Some of the facts obtained in these experiments are presented in this and the next chapter.

Apparatus for Current-voltage Measurements. — Figure 114 shows a sketch of a form of circuit employed in studying the conductivity of crystal contact under various conditions, by means of

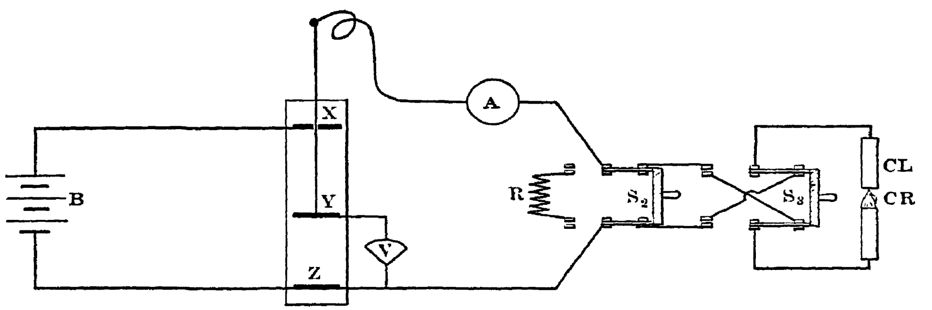

Fig. 114. Circuit for studying current-voltage characteristic of crystal rectifiers.

current and voltage measurements. The crystal, held in a clamp, is shown at *Cr*; *B* is a storage battery; *XYZ* is a potentiometer consisting of two fixed plates of zinc *X* and *Z*, and one movable plate *Y*, immersed in a zinc sulphate solution. By means of the voltmeter *V* the difference of potential between the plates *Y* and *Z* could be read, and the resulting current through the crystal was given by a galvanometer or milliammeter at *A*. The resistance of the galvanometer was so small in comparison with the resistance of the crystal that the reading of the voltmeter was practically the drop of voltage in the crystal.

The switch S_3 enables the observer to reverse the current in the crystal under examination without reversing the galvanometer. A known resistance at *R* could be thrown into circuit with the galvanometer for the purpose of calibrating it.

branch *II* the corresponding values of the current obtained when the voltage is reversed. The accompanying table, Table III, contains the numerical values from which these curves were plotted.

In the experiment whose result is shown in Fig. 116 and Table III, the specimen of carborundum was held in a clamp under a pressure of about 500 grams, and it is seen from the table that the current in one direction is 100 times as great as the current in the opposite

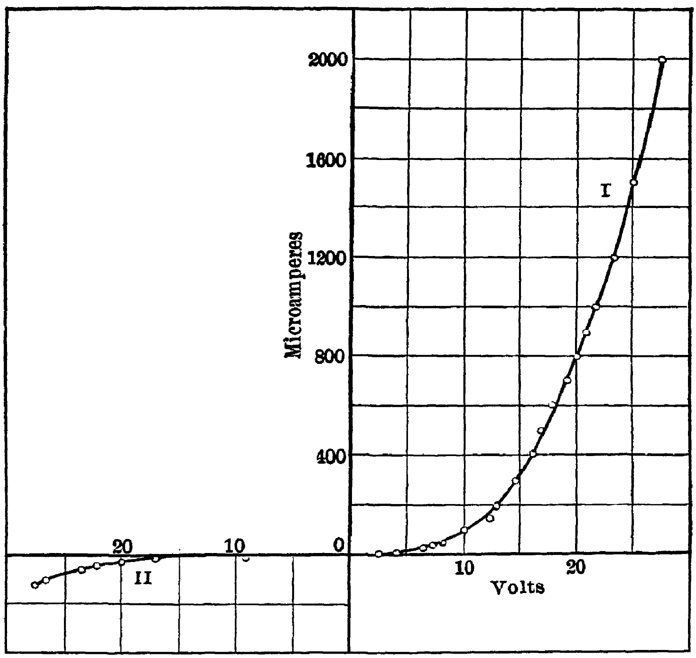

FIG. 116. Curve showing the carborundum contact to be unilaterally conductive.

direction when an electromotive force of 10 volts is applied in the two cases. With increase of current through the specimen, the ratio of the current in the two opposite directions diminishes. At 27.5 volts C_1 is only 17 times C_2.

In this particular experiment the piece of carborundum was submerged in an oil bath designed to keep the temperature of the specimen constant. The piece of carborundum was held in a clamp, the jaws of which served to lead the current to the speci-

curves of Fig. 117 cannot be taken to represent a general occurrence.

For more details on the effect of pressure reference is made to the original publications in the *Physical Review.*

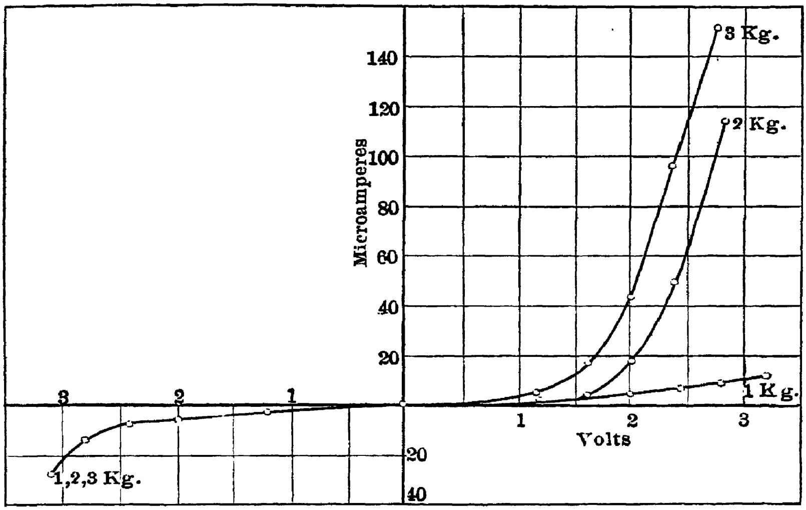

FIG. 117. Current-voltage curves of carborundum under different pressures.

Experiments with Platinized Specimens of Carborundum. — In the effort to ascertain what part the form of contact plays in the phenomenon of unilateral conductivity in crystals, a number of specimens of carborundum were selected with opposite faces plane and very approximately parallel, and some of the parallel-faced crystals were platinized on one or both of their smooth surfaces by the cathode discharge so that they could be put into good conducting contact with the electrodes. The metallic surfaces thus obtained were in many cases optically plane.

Platinized on One Face only. — Some of the specimens, platinized on one face only, gave very remarkable unilateral conductivity. Table IV shows results obtained with one of these specimens, designated 11_b, when submitted to a pressure of 1 kilogram. This specimen was .6 mm. thick, with area of about 1 sq. mm. One of the faces, which was optically true, was heavily platinized. The other face was somewhat rough and was without platinum. The specimen was held in a clamp with silver jaws.

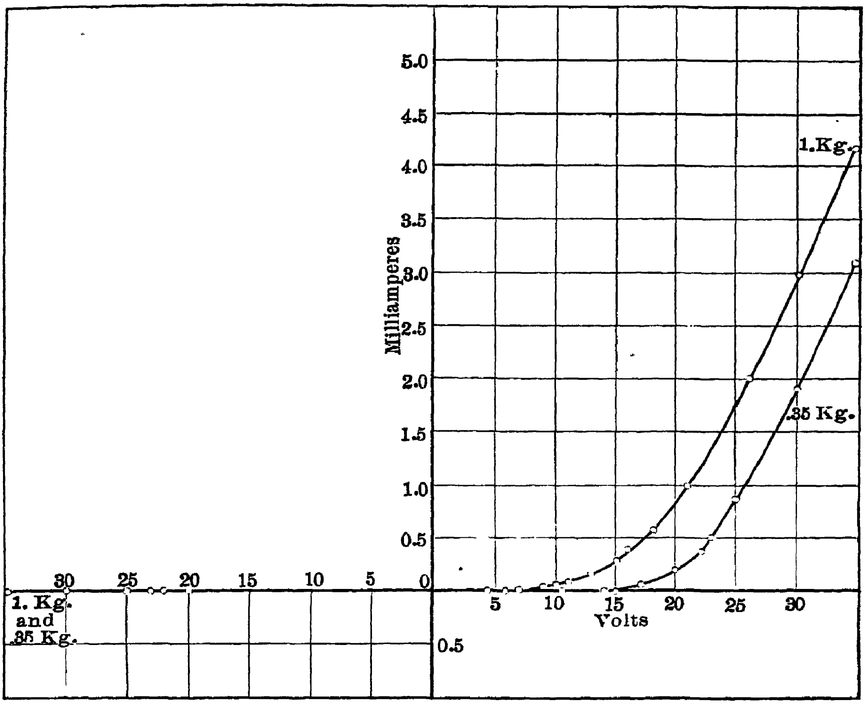

FIG. 118. Curve of a carborundum contact showing remarkable unilateral conductivity.

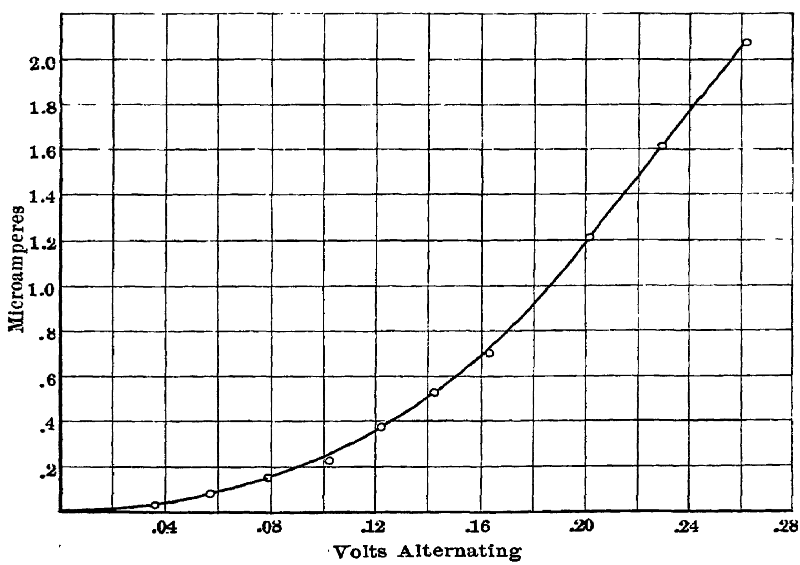

FIG. 119. Rectification of alternating current by a crystal-contact detector.

values of 60-cycle alternating voltage were applied to the circuit containing the detector and galvanometer in series. We shall present in a subsequent chapter some oscillograms obtained with the crystal rectifiers. Let us, however, first see how a rectifier for small alternating currents may be a detector for electric waves.

RECTIFIERS AS DETECTORS

Having seen in the preceding paragraphs that certain crystal contacts are rectifiers of alternating current, let us now reconcile this characteristic of the sensitive contacts with their action as a detector for electric waves.

Two Characteristics. — For the purposes of this discussion [1] we need to fix our attention upon two important characteristics of the sensitive contacts above investigated.

First, the current is not proportional to the voltage; and second, the current in the two opposite directions is not the same under the same applied voltage.

A detector may possess one of these characteristics without the

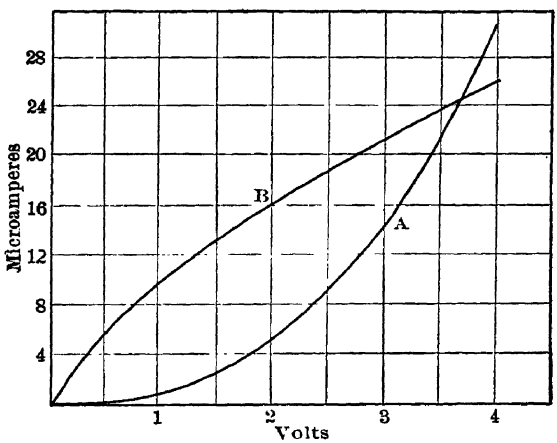

FIG. 120. Rising current-voltage characteristic (curve A) and falling current-voltage characteristic (curve B).

other, or may possess both together. A conductor or a combination of conductors possessing the first of these characteristics has,

[1] In this we are following very closely the arguments laid down by H. Brandes, Elektrotechnische Zeitschrift, Vol. 27, pp. 1015–1017, 1906, and Science Abstracts, No. 2078, Vol. 9, 1906.

an increment of direct current is obtained by the superposition of an alternating voltage upon the local direct voltage; that is to say, the apparatus is a *rectifier*.

In a similar way, it may be shown that if the conductor D has a *falling* characteristic, it also has a rectifying effect, if used with a local battery; but in this case the effect of the impressed alternating e.m.f is to produce a decrease in the local current.

Now a crystal contact which is *asymmetrically conductive* and has also a *rising* characteristic will be a rectifier without a battery and also with a suitable battery in the local circuit. Whether it will be a better rectifier with or without the battery depends on the form of the current-voltage characteristic.

WHY A RECTIFIER FOR SMALL ALTERNATING CURRENTS ACTS AS A DETECTOR FOR ELECTRIC WAVES

In the preceding sections we have seen that the detectors that have certain characteristics are rectifiers for alternating currents. In our illustration we applied our alternating e.m.f. directly to the circuit containing the detector and the galvanometer, or telephone, in series. But when the detector is used in a wireless telegraph receiving circuit, the alternating e.m.f. is not so applied, and furthermore has a very high frequency. How is the action of the detector to be explained in that case?

Let us take the case of the simple form of receiving circuit shown in Fig. 122, with or without a battery in the telephone circuit.

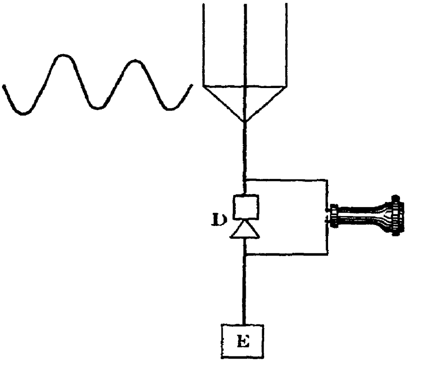

FIG. 122. Detector in antenna circuit.

A train of incoming waves produces an alternating e.m.f. in the antenna circuit. This e.m.f., when in one direction, produces a large current through the detector, D, charging the antenna. When the e.m.f. reverses, the current from the antenna to the ground through the carborundum is smaller, thus leaving the antenna charged with a small quantity of electricity. The effect of the whole train of waves is additive, so that this charge on the

CHAPTER XVIII

ON DETECTORS (*Continued*)

FURTHER EXPERIMENTS ON THE CRYSTAL RECTIFIERS

Having seen in the preceding chapter that the crystal contacts, when suitable crystals are employed are *detectors* for electric waves because they are *rectifiers* for rapid alternating currents, let us experimentally investigate the subject a little further.

Questions Arising in Connection with the Phenomenon. — Many interesting questions arise in connection with the phenomenon. Is the action localized at the surface of contact between the crystal and the metallic electrode ? Is the action due to electrolytic polarization? Is the action thermoelectric, conditioned on unequal heating of the two electrode contacts ? If the phenomenon is novel, how is it related to the hitherto studied properties of conductors?

In the experiments on carborundum, performed by the writer and partially presented in the preceding chapter, the investigation of these questions met with limitations on account of the form of occurrence of the carborundum in discrete masses to which electrodes could not be rigidly attached, so that the conditions at the electrodes could not be widely varied. However, by increasing the pressure of the electrodes against the carborundum beyond a certain limit, and by cathodically platinizing the surfaces of the carborundum at both the contact areas, we have seen that the rectification, though not entirely eliminated, was rendered very imperfect; that is to say, the ratio of the strength of the current in one direction to that in the reverse direction approached unity. On the other hand, platinizing one only of the surfaces of contact, while the other surface was left unplatinized, generally rendered the rectification more nearly perfect. This fact indicated that the seat of the action was the area of contact with the electrodes, and that the action at the two contacts were usually in opposition to each other, so that when the action at one of the contacts was reduced by platinizing, the rectification at the other contact appeared more pronounced.

action, it must be of such a character as to change the nature of the electrodes or of the crystal only very slowly, if at all.

On the Question of a Possible Thermoelectric Origin of the Phenomenon. — It is apparent that the disposition of the crystal, with a high-resistance contact of a metal against it at one side and usually a comparatively low-resistance contact at the other side, is exactly the most favorable for the development of heat at the high resistance junction. This heat being localized at a very small area, would raise the temperature of that area considerably. Now when the junction of two dissimilar conductors (e.g., bismuth and antimony) is heated, an electromotive force is developed at the junction. And for all we know, unless we try it, the contact of the crystal with the metal may have an enormously higher thermoelectromotive force developed than that developed at previously known thermal junctions.

If this is true, then when the current is in one direction the thermoelectromotive force would add to the applied voltage and produce an excessive current, while with the current in the opposite direction the thermoelectromotive force would subtract from the applied voltage and produce only a small current. This explanation of the phenomenon seems at first alluringly simple, and has been adopted by a number of writers and inventors, some of whom have, however, afterwards changed their views. But many persons still hold to the idea that these crystal-contact detectors are thermoelectric detectors, and they are so described in many trade catalogues, especially in Europe.

In fact, there is so much genuine circumstantial evidence in support of the thermoelectric hypothesis, that it seems very important to present with some thoroughness the experimental facts that exclude this hypothesis.

Extension of the Experiments to Other Crystals. — In order to carry out such an investigation a search was made for other crystals showing properties similar to carborundum but occurring in a form more suitable for study. After anatase and brookite and molybdenite had been discovered to be rectifiers and had been tested, it was found that the required conditions were best fullfilled by molybdenite.

I shall therefore describe the molybdenite detector. I shall then show and describe some oscillograms of alternating current through several crystal detectors, and shall afterwards return to some thermoelectric experiments.

shoulder of the cap, with the upper surface of the molybdenite exposed above. At the free surface of the molybdenite contact is made [1] with the metallic rod P.

The rod P was either supported unadjustably, as in the author's experiments on sound, or it was mounted in a manner to permit of ready adjustment, as is shown in Fig. 124. The clamp K containing the molybdenite is metallically connected with the binding post H (Fig. 124). Another binding post is attached

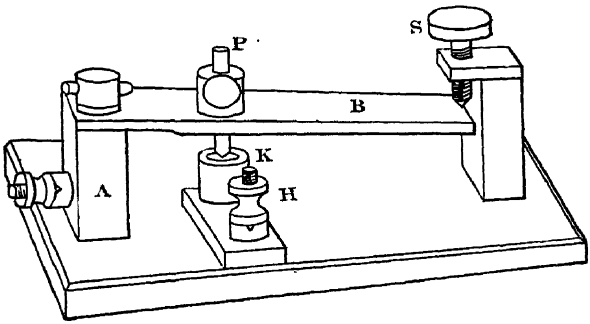

FIG. 124. Mounting for molybdenite.

to the metallic block A, on top of which is supported a stout spring B. Through a hole in B provided with a set-screw, the rod P is allowed to drop down into contact with the surface of the molybdenite at K. The set-screw is then tightened against P, and the final adjustment is made by the slow-motion screw S. The apparatus is connected in circuit by means of the binding posts, so that the current of the circuit is made to enter the molybdenite through the contact area between P and the molybdenite and leave by way of the contact between the molybdenite and the cap C, or the reverse. It is found that a much larger current flows in one direction than in the reverse direction for a given applied electromotive force.

The current-voltage curves (see Figs. 125, 126 and 127) resemble those of the carborundum detector, but large rectified currents

[1] In the diagrams of Fig. 123 and Fig. 124 the lower end of the rod P is shown pointed. It is found, however, that the end of the rod P may be blunt or even flat with an area as great as 4 sq. mm. without much loss of sensitiveness of the instrument as a receiver for electric waves or as a rectifier.

are obtained with very small voltages in the case of the molybdenite, which characterized the molybdenite rectifier as much more sensitive than the carborundum as a detector for electric waves.

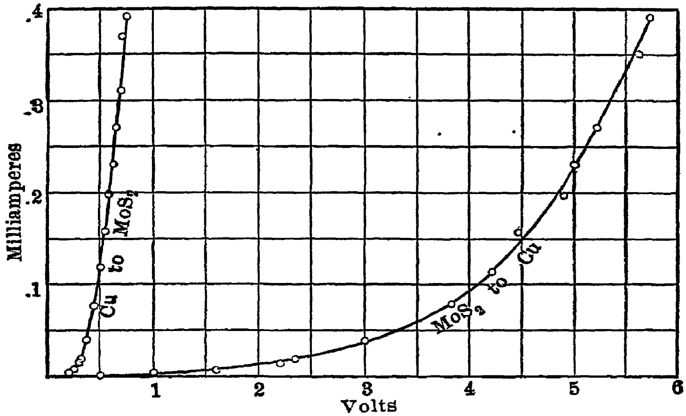

FIG. 127. Current-voltage curves with molybdenite rectifier.

OSCILLOGRAPHIC STUDY OF CRYSTAL RECTIFIERS

An oscillogram is a photograph showing the rapidly changing values of the current in a circuit when a rapidly changing voltage is applied to it. In the case of the crystal rectifiers a current of only a few thousandths of an ampere could be sent through the crystal contact without destroying its rectifying power. It was therefore necessary to employ a very sensitive apparatus, — one that would deflect with these small values of the current, and would reverse when the current reversed, and that at the same time would be so rapid in its action as not to show any appreciable lag when the current through it was rapidly changing. The purpose of the experiment was to see if the current changes in the detectors followed the voltage changes at once or if they lagged behind, as would be the case if the action of the detector depended on heating or cooling, because heating and cooling require time. Also, if electrolytic action entered into the phenomenon it ought to show in the oscillograms.

After much experimenting the necessary sensitiveness of apparatus was finally obtained with a Braun's cathode tubeoscillograph. This apparatus makes use of the fact that when a high electromotive force, say 20,000 volts, is applied to two aluminum electrodes sealed into a glass tube, from which the air is pumped to

could be made, during which time the image of the spot moved over the sensitive film 4800 times, without any failure of perfect superposition, and without any appreciable fogging of the film.

The deflecting electromagnets *MM* had a combined resistance of 436 ohms, and were provided with soft iron cores about 6 millimeters in diameter. With these deflecting coils a direct current of 1.5 milliamperes gave a deflection of 1 cm. on a ground glass put in the place of the sensitive film at the back of the camera. A calibration for different values of direct current through the coils showed the deflections of the light spot to be proportional to the current, for the small values of the current employed, and showed no evidence of hysteresis in the iron.

The Oscillographic Photographs. — Reproductions (reduced to $\frac{1}{3}$) of a characteristic set of the photographs obtained with a 60-cycle alternating e.m.f. are given in Plate I. Oscillograph No. 1 was taken with the molybdenite rectifier adjusted to give practically perfect rectification. No. 2 is with the same rectifier slightly out of adjustment (overloaded), so that the rectification is less perfect. No. 3 is with the same rectifier further out of adjustment. No. 4 is an oscillographic record with the carborundum rectifier. No. 5 is with the rectifier of brookite. In taking No. 2 the rectifier was submerged in oil, to test the effect of cooling.

Three Exposures. — In making these pictures the following steps were taken: The drum carrying the film was set rotating. The high-potential current obtained from Professor Trowbridge's 40,000 volt storage battery was started in the tube. The potential *V* (Fig. 128) and the contact of the rectifier were adjusted so that the deflection of the luminescent spot on the fluorescent screen showed good rectification. Exposure of about 2 minutes was then made. This exposure gave the heavy line of the oscillograms.

The switch at *T* (Fig. 128) was then thrown open, so that no current was flowing in the electromagnets and the luminescent spot came to its zero position. The exposure in this position was made for a shorter time of about 40 seconds. This traced a thin straight line along the centre of the picture and gave the axis of zero current.

The switch at *T* was then thrown to the position to put the resistance *R* in the circuit in place of the crystal. The resistance *R* had been previously adjusted, so that the amplitude of the deflection with *R* in the circuit should be equal to the maximum am-

plitude with the crystal in the circuit. With the resistance R in circuit an exposure of about 1 minute was made, giving the light sinusoidal curve of the picture.

On each picture the three exposures give, therefore, (1) the form of the rectified cycle as a heavy line, (2) the position of the axis of zero current, as a straight line through the figure, and (3) the form and position of the alternating current cycle when an

TABLE VI

TABULAR DESCRIPTION OF THE OSCILLOGRAPHIC RECORDS OF PLATE I

No.	Material of Rectifier.	Condition.	Maximum Rectified Current in Milliamperes.	R. M. S. Alternating Volts.	Equivalent Resistance in Ohms.
1	Molybdenite	Good adjustment	4.9	3.54	400
2	"	Out of best adjustment, submerged in oil and overloaded	4.9	3.54	400
3	"	Out of best adjustment	4.5		
4	Carborundum platinized on one side	Overloaded	5.4	22.0	6000
5	Brookite	"	3.0	2.22	992

equivalent resistance R is substituted for the rectifier. The last named cycle appears in the pictures as a thin-lined sine curve. This curve is in phase with the impressed voltage immediately about the crystal, and is referred to below as the "voltage-phase curve."

Coördinates. — In tracing all the curves, the motion of the light spot over the paper is from left to right; the time coördinate is, therefore, horizontal and is drawn as usual from left to right.

The scale drawn in ink at the left-hand margin of each picture gives the value of the current, one division being one milliampere.

Conditions. — A tabular description of the conditions under which each of the records was taken is contained in Table VI.

A discussion of the records follows:

Oscillogram Nos. 1, 2, and 3 — Molybdenite. — The pressure

differs from the molybdenite cycle in the absence of a lead at the negative maximum and at the point of rising from the zero axis. This anomaly in the case of the carborundum rectifier is seen later to be the effect of its high resistance.

Oscillogram No. 5 — Brookite. — The form of the cycle obtained in this case is intermediate between the carborundum cycle and the cycle of oscillogram No. 3. This is consistent with the value of its resistance.

In order to investigate the meaning of the lead of the rectified cycles in the several cases, the oscillograms had to be examined mathematically with the aid of the theory of alternating currents. Only the conclusions from this mathematical examination are here given. The mathematical reader is referred to the original paper.[1]

Conclusions from an Examination of the Rectified Cycle with the Aid of Alternating Current Theory. — (1) The case of the advance of the rectified cycle on rising from the axis of no current is shown in the mathematical discussion, above referred to, to be due to the fact that after a dormant half-period the current in the circuit follows the ordinary exponential " building-up " curve for a time before coming into coincidence with the sine curve. This building-up curve starts from the axis with zero lag, and is, therefore, in advance of the sine curve. It is chiefly due to the self-inductance in the oscillographic circuits. To this effect of self-inductance is to be added the effect due to the higher resistance of the rectifier for small currents than for large currents. This higher resistance brings the building-up curve a little nearer to the sine curve.

(2) The slightly quicker descent of the rectified cycle on approaching the axis after having traversed the upper half of the curve is also due to this higher resistance of the rectifier when traversed by smaller currents.

(3) The very significant lead of the negative maximum ahead of the corresponding voltage-phase maximum is explicable on the assumption that the rectifier has a much higher resistance in the negative direction than in the positive direction. We have shown in the mathematical discussion that the angle of lag of the voltage-phase cycle behind the impressed voltage, determined by the

[1] G. W. Pierce: Physical Review, 1909, Vol. 28, p. 153; or Proc. Am. Acad. of Arts and Sciences, 1909, Vol. 45, p. 317.

the result obtained in an oscillographic study of the electrolytic detector, where an integrative action was discovered (see next chapter).

THERMOELECTRIC PROPERTIES OF MOLYBDENITE

In the present section an account is given of the investigation of the thermoelectromotive force of molybdenite against copper and a determination of the temperature coefficient of resistance of molybdenite. Apart from their possible bearing on the action of the rectifier, the thermoelectric properties of molybdenite are of interest in themselves.

Thermoelectromotive Force. — Five specimens were mounted for the study of the thermoelectromotive force of molybdenite against copper. These specimens are referred to as "A," "B," "C," "D," and "E." The method of mounting the specimen *E* is shown in Fig. 129. A thin sheet of molybdenite .1 or .2 mm.

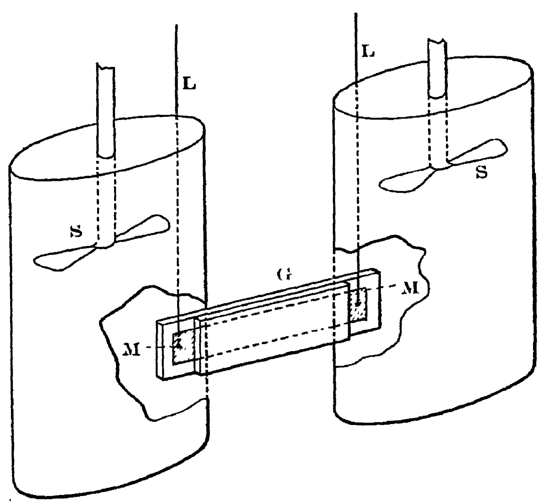

Fig. 129. Apparatus for studying thermoelectric properties of molybdenite.

thick, 2 cm. wide, and 8 cm. long, was cemented between two glass microscope slides *G* with a cement made of water-glass and calcium carbonate. The molybdenite was then copper-plated over a small area at each of the exposed ends *MM*, and to these copper-plated areas were soldered copper wires .2 mm. in diameter, so as to form

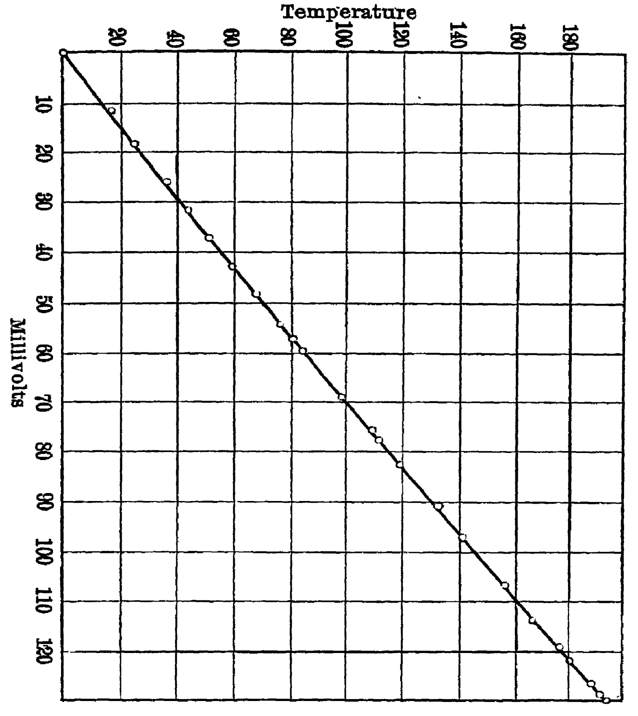

FIG. 130. Curve of thermoelectromotive force of molybdenite (specimen *E*) against copper, for various temperatures of the hot junction.

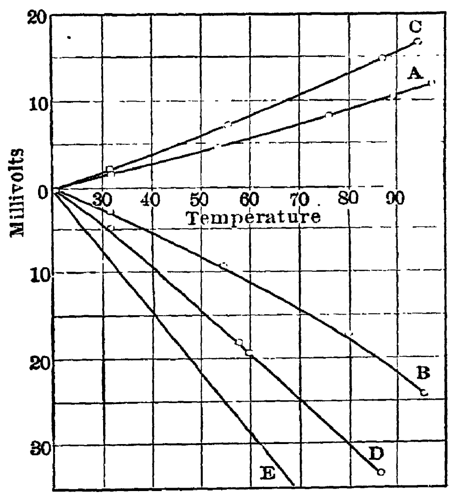

FIG. 131. Thermoelectric curves of various specimens of molybdenite against copper.

other. *This preliminary test proved very interesting in that it showed that one may find all over many of the pieces cut from a crystal of molybdenite points where the substance is thermoelectrically positive and other points where it is thermoelectrically negative.* These positive and negative points sometimes lie so near together that with a fine-pointed exploring electrode attached to a galvanometer and warmed by heat conducted from the hand, one may find the deflections of the galvanometer reversed from large positive values to large negative values on making the slightest possible motion of the pointer over the crystal.

Explorations of this kind failed to show any definite orientation of the thermoelectric quality with respect to the crystallographic axes.

The existence of small thermoelectrically positive and negative patches in a piece of the molybdenite may indicate that the thermoelectromotive force measured by attaching wires to the specimen is too low on account of the inclusion under the electrodes of both positive and negative areas which would partially neutralize the thermoelectric action against another electrode.

TABLE IX

Substance.	Thermoelectromotive Force in Microvolts, per Degree Centigrade, at 20° C.		Authority.
	Against Copper.	Against Lead.	
Molybdenite A....	110	113	Present experiment
” B...	−230	−227	”
” C...	175	178	”
” D....	−415	−413	”
” E...	−720	−717	”
Silicon...........		−400	Frances G. Wick [1]
Bismuth.........		− 89	Matthiessen [2]
Antimony........		26	”
Tellurium.........		502	”
Selenium.........		807	”

[1] Phys. Rev., 25, 390. [2] Everett, Units and Physical Constants.

It may be said in passing that the specimens *D* and *E*, *with soldered connections*, still showed the phenomenon of rectification when used with alternating currents, even when the two junctions of the copper with the molybdenite were in oil baths at the same

20° the decrease of resistance per degree increase of temperature is 1.19 percent.

Plausibility of Thermoelectric Explanation. — The large thermoelectromotive force of the molybdenite against the common metals, together with its large negative temperature coefficient of resistance, lends plausibility to the hypothesis that the rectification is due to thermoelectricity. For if we pass an electric current through the rectifier and the current begins to make its way

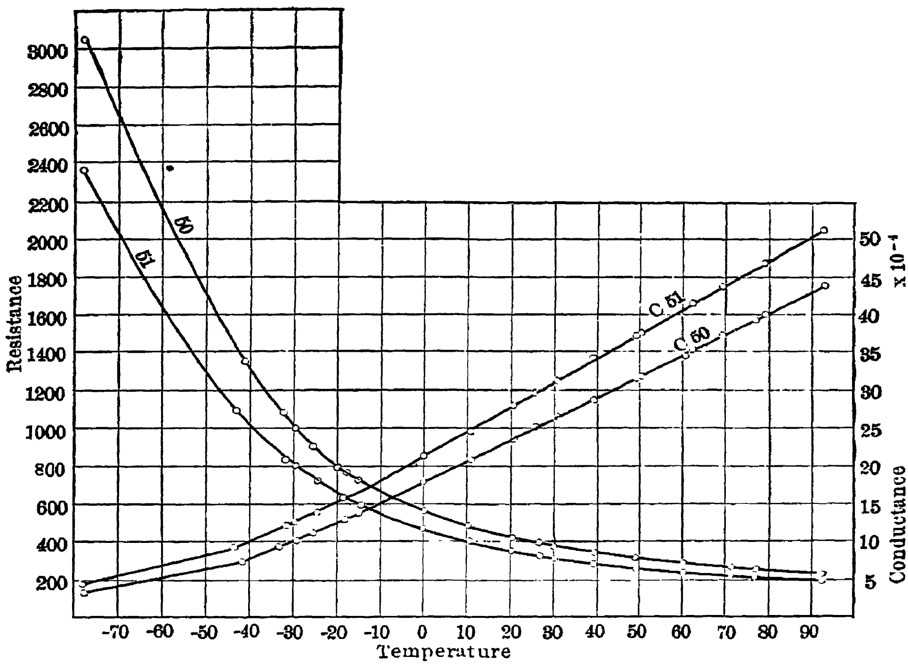

FIG. 132. Resistance and conductance of molybdenite as a function of the temperature.

through a small area at the contact, this small area is heated and decreases in resistance, so that the greater part of the current flows through this particular small area, heating it still more, while the portions of the contact through which the current has not started remain cool and continue to offer a high resistance. The effect of this action is to confine the heating to an extremely small area, which is the condition necessary for the extremely rapid and efficient action of the rectifier, on the hypothesis of a thermoelectric explanation. That there is, however, an insuperable ob-

denite or the circuit through the constantan could be read on the galvanometers *A* or *G*. Also the rectified current obtained by applying the alternating voltage *V* could be read on the galvanometer *A*. When the thermal current or the rectified current through *A* is in the direction of the arrow *B*, the molybdenite, following the usage in thermoelectricity, is said to be *positive.* When the current in *A* is in the direction opposite to the arrow *B*, the molybdenite is said to be *negative.*

The results obtained with a number of specimens of molybdenite when heat was applied *above*, and when heat was applied *below*, and when the *alternating voltage* was applied, are contained in Table X.

TABLE X

SIGN OF MOLYBDENITE WHEN HEATED ABOVE OR BELOW AND WHEN SUBJECTED TO ALTERNATING VOLTAGE

Specimen No.	Heated Above.	Heated Below.	Under Alternating Voltage.
75	+	−	−
81	+	−	−
Turned over	+	−	−
93	−	+	+
Another point	−	−	+
”	−	−	+
Turned over	−	−	+
78	+	+	+
Another point	+	−	−
”	+	+	−
94	−	−	+
Another point	−	+	+
”	−	+	+

From this table it appears that the thermoelectric voltage *when the junction is heated by heat conducted from above,* in twelve out of the thirteen cases tried, is opposite to the direct voltage obtained when an alternating current is passed through the junction. *When the heat is conducted to the junction from below, through the molybdenite,* the thermoelectromotive force in four cases is opposite to the rectified voltage, and in nine cases is in the same direction as the rectified voltage. In only one case, one point of No. 78, is the rectified voltage in the same direction as the thermal voltage, both when the junction is heated from above and when it is heated from below.

In all of these cases the heat was applied in the neighborhood of the same junction, and there is no opportunity for heat to get to

When, on the other hand, as a control experiment, heat was applied to the copper-molybdenite junction from below so that it had to be conducted through the molybdenite and through the copper-molybdenite junction to get to the copper-constantan junction, the heating shown by the auxiliary copper-constantan junction was 11.4° C., while the thermal current from the copper-molybdenite junction was only .2 microamperes. In both the case of the rectified current and the case of the application of heat from below the heat had to be conducted from the point of rectification to the auxiliary junction. Therefore, with a rise of temperature of the auxiliary junction 1100 times as great as the rise shown during the rectification, the thermal current in the copper-molybdenite circuit was $\frac{1}{500}$ of the rectified current; that is to say, the rectified current, for a rise of temperature of $\frac{1}{100}$ of a degree of the auxiliary junction (being approximately a linear function of the temperature) was less than $\frac{1}{500000}$ of the rectified current from an alternating current producing the same rise of temperature.

Summary of Conclusions from the Experiments with the Crystal Rectifiers. — 1. An examination of the characteristics of contact detectors using carborundum, anatase, brookite, hessite, iron pyrites, and silicon shows that we are dealing with the same kind of phenomenon in the case of all these crystal substances. The various other crystal-contact detectors which I have not examined probably act in the same way.

2. At the contact between the crystal and a common metal, or between two different crystals, or between two apparently similar crystals, there is asymmetric conductivity, permitting a much greater current to flow in one direction than in the other under the same applied voltage.

3. These contacts all have a rising current-voltage characteristic.

4. These crystals all have a large thermoelectromotive force against the common metals, and the amount and the direction of this thermoelectromotive force is different at different points on the crystalline bodies.

5. The rectifying effect is also different in amount and direction at different points of the crystalline body; the direction of the rectifying effect is often opposite to the effect that would be obtained by heating the contact.

6. Thermoelectricity does not explain the phenomenon of rectification, but the two effects, since both exist in such marked

CHAPTER XIX

ON DETECTORS (*Concluded*)

THE ELECTROLYTIC DETECTOR, AND VACUUM DETECTORS

Description of the Electrolytic Detector. — The electrolytic detector for electric waves, as described by Fessenden [1] and shortly after by Schloemilch,[2] consists of a cell containing an electrolyte and having one electrode of very small area, usually in the form of an extremely fine wire of platinum, and as the other electrode a larger area of platinum or some other metal. When used in wireless telegraphy the two electrodes are connected in a circuit upon which the electric oscillations are impressed, so that the rapidly oscillating electric currents in the circuit are made to traverse the cell of the detector. An example of a simple form of receiving circuit, with the detector connected in the antenna, is shown at *MDG* of Fig. 134. A local circuit *TED*, through the detector, contains a telephone receiver *T* and an adjustable source of e.m.f., which is used to polarize the detector by sending through it and the telephone a small direct current. Under the action of the electric oscillations through the detector the current in the telephone receiver is modified so as to produce a sound in the telephone with a period determined by the train frequency of the incident electric waves. The action is localized at the contact of the fine wire with the electrolyte.

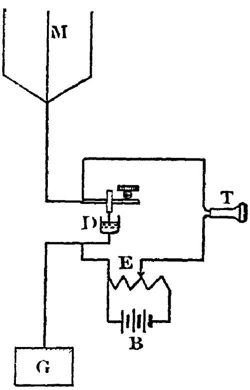

FIG. 134. Circuit with electrolytic detector.

Details of the Electrolytic Detector. — The electrolyte employed in the electrolytic detector is usually 20% nitric acid, though almost any electrolytically conductive liquid (e.g., dilute sulphuric acid, common salt solution, caustic soda, etc.) may be used. For a highly sensitive detector the fine platinum wire employed as

[1] Fessenden, U. S. Patent, No. 727,331, filed April 9, 1903; issued May 5, 1903.

[2] Schloemilch, Elektrotechnische Zeitschrift, Vol. 24, p. 959, Nov. 19, 1903.

This makes the detector itself a primary battery.

This arrangement for which a United States patent has been issued to Schloemilch,[1] and also to Shoemaker,[2] would seem to be incapable of the high sensitiveness attained by the form in which the accurately adjustable external voltage, as in Fig. 134, is employed.

Regarding the Theory of the Electrolytic Detector. — Considerable diversity of opinion has been expressed by various writers as to the manner in which the electrolytic detector acts as a receiver for electric waves. Professor Fessenden in his original patent attributes the action to heat, and he calls this form of detector a "liquid barretter." Professor Armagnat,[3] who has made an experimental study of the subject, attributes the action to a rectifying effect resulting from polarization. Armagnat obtained a curve of the form of Fig. 137 for the current-voltage characteristic of the electrolytic detector. Dr. L. W. Austin [4] also found that the electrolytic detector acted as a rectifier for small alternating currents, but came to the opinion that heat, chemical action, rectification, and electrostatic attraction across the gas film might have a part in the explanation of the phenomenon when the detector was used with electric waves.

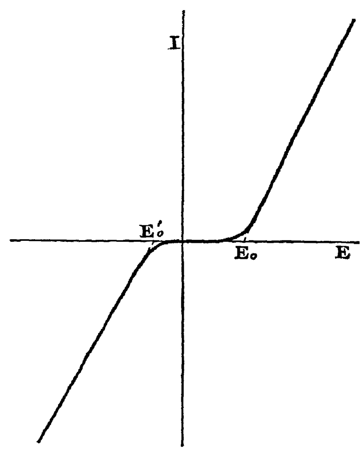

FIG. 137. Current-voltage curve of electrolytic detector.

A doubt that arose in the minds of some investigators of the subject as to a possible explanation of the phenomenon in terms of rectification alone came, it seems, from the idea that there could not be energy enough in the electric waves received at great distances to produce the effects in any other way than by a triggering action, by which the local energy of the battery was

[1] Wilhelm Schloemilch, U. S. Patent, No. 936,258, filed Oct. 3, 1903, issued Oct. 5, 1909.

[2] Harry Shoemaker, U. S. Patent, No. 795,312, filed Feb. 13, 1905, issued July 25, 1905.

[3] Armagnat, Bul. soc. française, session of April, 1906, p. 205; Journal de Physique, Vol. 5, p. 748, 1906.

[4] Austin, Bul. Bureau of Standards, Vol. 2, p. 261, 1906.

This quotation shows that Pupin had employed the electrolytic detector in 1899 as a rectifier for electric waves of Hertzian frequency, and that he had a well-defined explanation of the processes occurring in the rectifier. I have made some experiments that fall into close agreement with Pupin's explanation of the phenomenon. These are described in the succeeding paragraphs.

OSCILLOGRAPHIC STUDY OF THE ELECTROLYTIC DETECTOR[1]

In these experiments the current through the detector under the action of an alternating e.m.f., superposed on a polarizing current, is determined by means of an oscillograph. The application of the oscillograph to the problem gives the instantaneous values of the current through the detector, and permits an examination of the wave form of the rectified cycle. The oscillographic apparatus was the Braun's tube described in Chapter XVIII.

Circuits Employed with the Detector in Taking the Oscillograms.— The electrolytic detector used in these experiments made

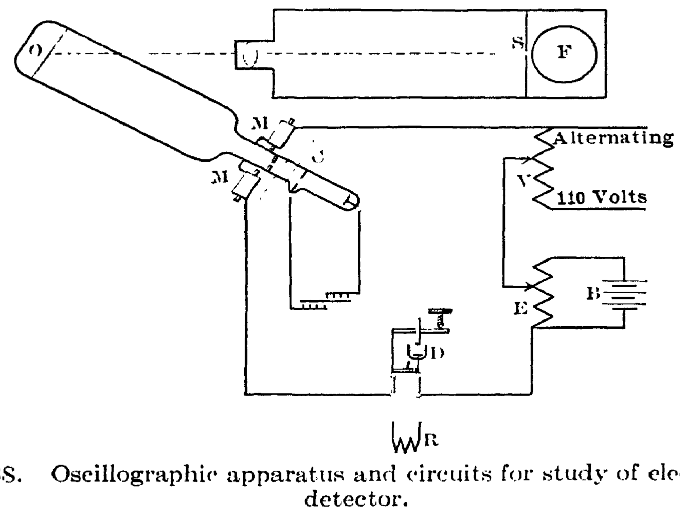

FIG. 138. Oscillographic apparatus and circuits for study of electrolytic detector.

use of a platinum point, .0002 inch in diameter, dipping into 20 per cent nitric acid, and was adjusted to high sensitiveness as an electric wave detector immediately before taking the oscillograms. A diagram of the circuits employed in the experiment, together with a sketch of the oscillographic apparatus, is shown in Fig. 138.

[1] This account is an abridgment of an article by the author on "The Electrolytic Detector, Studied with the Aid of an Oscillograph." Physical Review, 1909, Vol. 28, p. 56.

about the detector.[1] A similar curve was made use of in the experiments of the preceding chapter and is there discussed. In the present experiments, because of the employment of the polarizing current with the rectifier, a question arises as to the appropriate method of taking this cycle. Two different methods were tried, either of which, by proper elimination of the constants of the oscillographic apparatus, will give the desired result. The method yielding simplest results for the voltage-phase cycle is the following: After the exposure for the rectified cycle had been made, the alternating voltage was left unchanged, and a resistance was substituted for the rectifier. A double adjustment of the substituted resistance and the direct voltage was made by successive approximations until the result was attained that (1) the direct voltage alone gave through the substituted resistance a current equal to that used in polarizing the rectifier and (2) the alternating voltage superposed on this direct current gave a deflection of the luminescent spot to a point coincident with the maximum point attained with the rectifier in the circuit. This means that the voltage-phase cycle was taken with the axis of polarizing current as axis, and with amplitude equal to the maximum amplitude of the rectified cycle. This method was employed in oscillograms 1, 2, and 5.

The second method of taking the voltage-phase cycle was as follows: The polarizing voltage was reduced to zero, the detector was short-circuited, and an alternating voltage equal to that used with the detector was applied to the circuit. This method was employed in oscillograms 3 and 4.

Coördinates of the Oscillographic Curves. — In taking all of the curves of the oscillograms, the motion of the light spot over the film is from left to right; the time coördinate is, therefore, the horizontal scale of the curves and is drawn as usual from left to right. The current coördinate is given in the scale drawn in ink at the left-hand margin of each picture — one division being one milliampere.

DISCUSSION OF THE OSCILLOGRAMS OF PLATE II

The oscillograms shown in Plate II are reproductions of positives printed from the films carried by the rotating drum. They were taken with a 60-cycle alternating current applied to the circuit

[1] The ordinary method, which would be to take the leads from the two sides of the detector through a high resistance to the oscillograph, could not be used because the oscillograph was working at the limit of its sensitiveness on the full voltage without the added resistance.

containing the electrolytic detector. The reproduction is one-third the size of the original. The several curves shown in the plate were obtained with different polarizing currents superposed on the circuit. Table XI contains a tabulation of the polarizing current and voltage, the applied alternating voltage, the maximum current through the detector, and the substituted resistance employed in taking the voltage curve.

TABLE XI

TABULAR DESCRIPTION OF THE OSCILLOGRAPHIC RECORDS

No.	Polarizing Direct Current in Milliamperes.	Polarizing E.M.F. in Volts.	R.M.S. Volts A.C.	Maximum Positive Current through Detector in Milliamperes.	Equivalent Resistance in Ohms.
1[1]	.1	1.45	2.09	2.37	440[1]
2	1.0	5.5	4.00	9.6	70
3[2]	1.2	5.5	4.00	9.6	00[2]
4[2]	1.4	Not measured	5.00	10.0	00[2]
5	2.2	”	5.00	11.0	150

[1] It should be noticed that the sensitiveness of the oscillograph when No. 1 was taken was three times as great as when the other oscillograms of the plate were taken.

[2] The voltage-phase cycle of oscillograms 3 and 4 was taken with the polarizing current omitted, so that they have the axis of no current as axis of the cycle.

Point Anode or Cathode — the Large Loop in the Direction of the Polarizing Current. — Some of the oscillograms were taken with the polarizing current from the point to the electrolyte and some with the polarizing current in the opposite direction. Although the values of the polarizing voltage required to produce a given polarizing current were different in the two cases the general characteristics of the cycle were the same. A reversal of the polarizing current reversed the rectified current, and whether the polarizing current was from the point to electrolyte or in the opposite direction the large loop of the rectified cycle (always oscillographed positively) was obtained when the alternating current was flowing in the same direction as the polarizing current.

The Form of the Rectified Cycle. — The cycle obtained with the rectifier in the circuit has the same general form in all the pictures. When the current, having traversed the positive loop, comes to the axis of zero current, it follows along this axis for a short way,

region to the immediate right of the negative maximum. This rise is more striking in the original photographs than in the reproductions; and, though small, it deserves attention, because the occurrence of this small positive maximum is evidence of the existence for about $\frac{1}{1500}$ of a second of a positive e.m.f. greater than the e.m.f. immediately following. Now in this part of the cycle the externally applied e.m.f. is greater following the rise than during the rise; therefore the rise indicates the existence of a positive e.m.f. in the circuit itself. This is capable of the following explanation in terms of the theory of polarization. After the prevalent external e.m.f. has been in a negative direction and has returned to zero, the polarization tension which has been opposing the negative current at the electrode continues to exist for a short time and produces a positive current. This action, resembling that of a capacity, is familiarly known as the *polarization capacity* of the electrode. By the existence of the small positive maximum near the axis of the cycle, the oscillogram shows that the polarization capacity of the electrode is not entirely negligible. Evidence of the existence of this polarization capacity is clearly given by the oscillograms 1, 2, and 3. The oscillograms 4 and 5, while not having a positive maximum near the axis, show also a striking tendency toward a maximum at this point, which is, however, masked by the rapid rise of the building-up curve in this part of the cycle.

CONCLUSIONS IN REGARD TO THE ELECTROLYTIC DETECTOR

1. The whole phenomenon of the rectification of small alternating currents by the electrolytic detector seems to be explicable in terms of the theory of electrolytic polarization.

2. The polarization capacity of the small platinum electrode is not entirely negligible, even with currents making only 60 cycles per second. The polarization capacity may, however, aid in producing a rectified current as well as in opposing this effect, and apart from the effect of this capacity on the tuning of the circuit, does not detract from the utility of the rectifier as a detector for electric waves.

3. The present conclusions in regard to the action of the detector are entirely in accord with Pupin's original brief description of the phenomenon as quoted above.

current through it, negative electrons are sent off from it and render the space between the filament and the cylinder conductive for an electric current, provided the e.m.f. producing this current is directed from the cylinder to the hot filament. In case the e.m.f. is applied in the opposite direction, no current, or a much smaller current, flows. An oscillating e.m.f. applied to the cylinder and filament produces more current in one direction than in the opposite direction.

One method of connecting the valve into a wireless telegraph receiving circuit is shown in the diagram, which is taken from

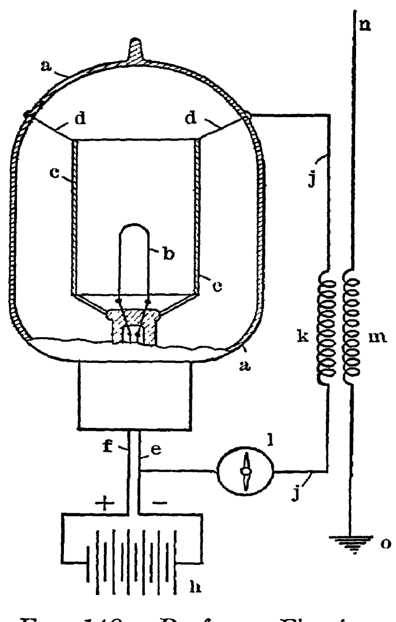

FIG. 140. Professor Fleming vacuum tube rectifier.

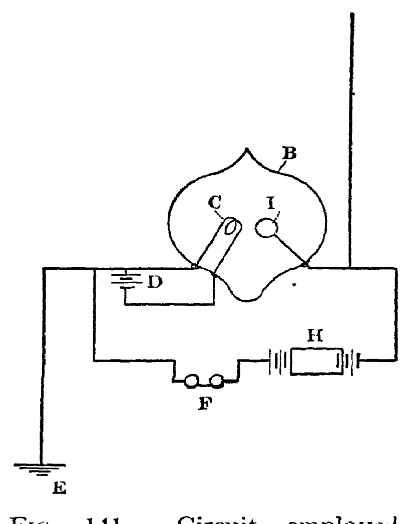

FIG. 141. Circuit employed by Dr. DeForest with vacuum detector.

Professor Fleming's U. S. Patent Specifications. Here the valve is in a circuit connected inductively with a wireless telegraph antenna. Electrical oscillations in the antenna induce an oscillating electromotive force in the coil *k*, and this oscillating e.m.f. sends more current in one direction than in the opposite direction through the valve and through the current-indicating instrument *l*.

A modification of the method of connecting the indicating instrument to the *oscillation valve* has been made by DeForest so as to permit the use of a telephone as indicator. A diagram of

CHAPTER XX

ELECTRICAL RESONANCE

WAVE METERS. RESONANCE IN SIMPLE CONDENSER CIRCUITS

On account of the multiplicity of facts requiring presentation in an elementary discussion of electric wave phenomena, it is often difficult to decide what is the most direct course to follow. For a part of the way, in the earlier chapters, we were able to proceed almost in the historic order. Up to about the year 1900, the growth of knowledge of electric waves, so far as pertains to wireless telegraphy, occurred as a fairly direct sequence of important events, which have been sketched in Chapters I to XIII. About the year 1900 the literature of the subject began to multiply enormously and practical progress began to develop in many directions. Two main branches of this development we have already pursued, in a discussion of the propagation of the electric waves to long distances over the surface of the earth and in a discussion of some of the detectors used in receiving the signals. We shall now begin the study of a third main branch of the subject; namely, Electrical Resonance.

Introduction to a Study of Electrical Resonance. — In previous chapters attention has been called to the importance of bringing different parts of the sending and receiving circuits into resonance with one another. By this means the strength of the signals is increased, and the interference arising when several stations are operated simultaneously is partially eliminated.

The main elements of variation in attuning circuits one to another are inductance and capacity. Preparatory to the study of more complex cases of resonance, let us recall the experiments of Sir Oliver Lodge, described in Chapter VIII, in which two Leyden-jar circuits were attuned to each other. One of the Leyden-jar circuits, which I shall call the oscillating circuit, was provided with a spark gap, and was charged by an electric machine and allowed to discharge. The other Leyden-jar circuit (compare Fig. 142) was at a distance of perhaps a meter or two from the oscillating circuit, and could be adjusted as to period of vibration by a

tory circuit, and by adjusting the slider S of Circuit II this circuit may be brought into resonance with the Circuit I of unknown period. The condition of resonance is indicated by the maximum glow in a sensitive vacuum tube in contact with one of the plates of the condenser of the frequency meter. When this resonant

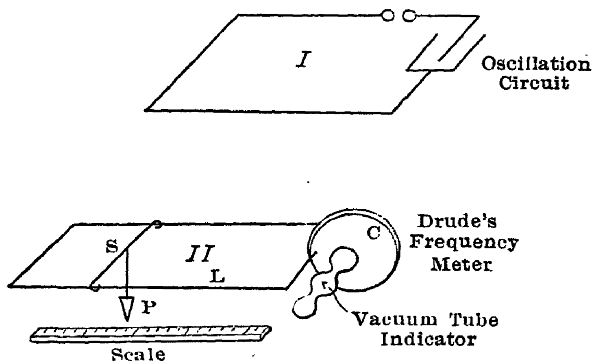

Fig. 143. Drude's resonant method of measuring wave-length and frequency.

adjustment has been made, the position of the pointer P on the scale is read, and from this reading the period of the frequency meter is known, for by calculation Drude has calibrated the frequency meter in terms of the period corresponding to any particular adjustment of the pointer on the scale.

The period of the frequency meter at resonance is the same as that of the oscillating circuit; which is, therefore, also known.

Likewise, the wave length in air that Circuit I emits is known, for this wave length is the velocity of light times the period.[1]

In terms of units,

$$\text{Wave length in meters} = 3 \times 10^8 \times \text{period in seconds}.$$

By means of this apparatus Drude was able to determine wave lengths between 2 and 445 meters.

Doenitz's Wave Meter. — Dr. Johann Doenitz [2] of Berlin, Germany, has constructed a wave meter that is in a very compact and convenient form for measuring the wave lengths of wireless telegraphy. Instead of a gradually variable inductance, as in Drude's apparatus, Doenitz's instrument has a gradually variable condenser

[1] See Chapter X.

[2] *Elektrotechnische Zeitschrift*, Vol. 24, pp. 920–925, 1903. German Patent, No. 149,350, from April 4, 1903. U. S. Patent, No. 763,164, filed Sept. 15, 1903, issued June 21, 1904.

approaches resonance with the oscillating circuit whose wave length is to be measured. Resonance is determined by noting the amount of current in the wave-meter circuit. This is done by means of a Harris or Riess hot-wire air thermometer h, which is, however, not connected directly into the wave meter circuit, but is coupled with it by means of the oscillation transformer $i\,i_1$. The action of this transformer and thermometer is as follows: The primary i of the transformer is in the wave-meter circuit; the secondary i_1 of the transformer is in series with a resistance w, designed to be heated by the current through it. This heating of the resistance heats a quantity of air in a glass bulb surrounding the resistance, causing this air to expand, and to push up a column of mercury in the bent tube h. As the wave meter approaches resonance with the oscillation circuit, the rise of the column of mercury in the bent tube increases.

By reading this indicator, not only can one determine the resonant adjustment of the wave-meter circuit, but one can also form some idea of the sharpness of resonance by noting whether small or large variations of the condenser are required for a given rise of the indicator.

The range of wave lengths measurable by Doenitz's wave meter is changed by substituting various coils of different numbers of turns for the receiving loop s. For each of the coils there is a corresponding calibration of the scale.

Sample of Observations Made with a Doenitz Wave Meter. — The curves of Fig. 145 were obtained [1] by a Doenitz wave meter. The curves show the scale reading of the air thermometer for various settings of the wave meter. Curve I was obtained by tuning the wave meter to an oscillating antenna circuit; Curve II was obtained by tuning the wave meter to an oscillating condenser circuit. The condenser circuit and the antenna circuit are seen to have the same wave length, 320 meters, indicated by the fact that this value, 320 meters, is the reading of the wave-meter scale when the thermometer scale reading is a maximum. Now when the two circuits of curves I and II were coupled together, and the wave meter applied to a study of the oscillations occurring in the coupled system, the results plotted in Curve III were obtained. The resonance curve in this case has two maxima. To this subject we shall return.

[1] Figure 145 is copied with some slight modifications from Lieutenant-Commander S. S. Robison's Manual of Wireless Telegraphy, 1906.

An advantage of Fleming's cymometer over other forms of wave meter arises in the fact that the scale readings are nearly proportional to the wave length (giving a nearly uniform scale when calibrated in wave lengths), whereas with instruments of the Doenitz type the wave length is nearly proportional to the square root [1] of the capacity of the adjustable condenser, so that the divisions on the scale become wider apart as the wave length increases.

Fleming's instrument has, however, the disadvantage of lack of compactness, for the inductance and condenser of this instrument are from one to two meters long.

Pierce Wave Meter. — I have designed a wave meter that has met with some use in practical application to wireless telegraphy. It consists of a Korda semicircular plate condenser C (Fig. 147), in series with a loop L for receiving the inductive action, and in

FIG. 146. Fleming cymometer.

series with a specially constructed high-frequency telephone receiver T. A pointer carried by the axle of the movable plates of the condenser passes over a scale, which is calibrated directly in wave lengths.

At resonance, a maximum sound is produced in the high-frequency telephone receiver. On account of the high sensitiveness of the telephone receiver the wave length of currents in which the oscillations are extremely feeble may be determined, and also, on account of this high sensitiveness, the condenser can be made very compact and light, so that the whole instrument in the standard form weighs only 14 pounds.

[1] This the reader may verify by examining the formula $\lambda = 2\pi v\sqrt{LC}$.

an accurate device, called a "stroboscope," for determining the period of revolution of the mirror.

Having the period of revolution of the mirror and the distance between spark-terminal images on photographs like those of Fig. 3, one has a direct measurement of the period T of the discharge of a given oscillating circuit. By constructing a large number of such oscillatory discharge circuits giving various periods of discharge, or, better, by using a discharge circuit whose period could be varied at will, one may obtain accurate values of various periods by the use of the revolving mirror; and from the various periods T one can obtain the wave length λ in air of the emitted wave by the formula

$$\lambda = v \times T,$$

where $v = 3 \times 10^8$ meters per second, T is the time in seconds of one complete oscillation of the circuit, and λ is wave length in meters.

The wave meter to be calibrated is now set to resonance with each of these known wave lengths and the wave length is written at its appropriate position on the scale of the instrument.

Another method of calibrating a wave meter is by tuning it to resonance with circuits of which the period is known by calculation from a knowledge of capacity and inductance.

Method of Using a Wave Meter. — Let it be required to determine the wave length in air emitted by the oscillation circuit S,

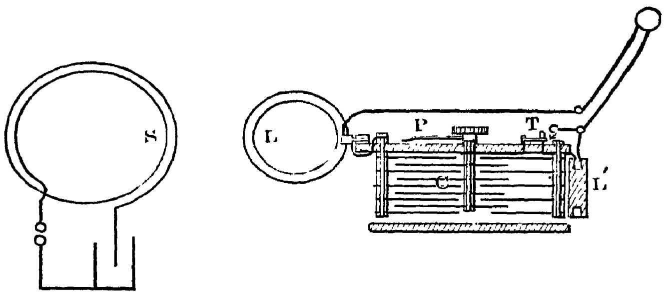

FIG. 148. Position of wave meter for determining the wave length or frequency of the circuit S.

Fig. 148. The wave meter must be placed in such a position that the magnetic force from S links with the loop L of the wave meter; the oscillations in S then act inductively on the wave meter. This action is a maximum when the loop L is close up to S and in a plane parallel with it. It is, however, not advisable to have the two circuits too close together, because in this case the oscillations

The last column contains eight independent determinations of the capacity with an average error of only 1%.

This is one of the best methods of determining the capacity of a condenser under conditions of actual use.

Effect of Resistance on the Sharpness of Resonance. — In tuning a condenser circuit with adjustable capacity or inductance to resonance with an oscillating circuit, as was done in the wave-metrical experiments above described, we have a simple case of the kind of tuning that is made use of at a receiving station when it is desired to receive signals of one wave length and exclude signals of a different wave length.

One of the main difficulties in completely excluding undesired signals arises from the fact that the detectors used in receiving the signals have a high resistance.

Let us see how the sharpness of resonance is affected by resistance of the receiving circuit, in the simple case in which a condenser circuit (e.g., the wave-meter circuit) is attuned to a given wave length.

As an example, I shall take a case in which the constants of the receiving circuit are within the range employed in wireless telegraphy. In Fig. 149 suppose that L is an inductance of .0001 henry, I an instrument for measuring the oscillatory current (root of mean square current) produced by an incoming electric wave, which is supposed to have a wave length $\lambda_1 = 300$ meters; C is a variable capacity, and this capacity is supposed to be calibrated directly in wave lengths, λ_2. Let the receiving circuit be set at various wave lengths and let the corresponding current be read on the instrument I.

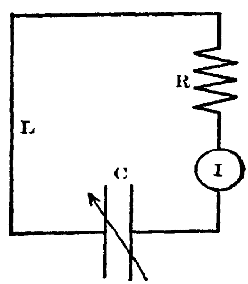

FIG. 149. Simple oscillation circuit.

By a calculation that is not here reproduced, it can be shown that the results plotted in Fig. 150 will be obtained. The relative current is plotted vertically, while the settings of the wave length of the receiving circuit divided by the wave length of the incident wave (λ_2/λ_1) are plotted horizontally.

The different curves in the diagram show the effects of putting different values of the resistance R into the receiving circuit. A maximum current is received in each case when $\lambda_2 = \lambda_1$, but the sharpness or flatness of the curves depends on the value of R. When $R = 628$ ohms the top curve is obtained. This curve is nearly

In this problem I have supposed that the waves which are arriving are themselves undamped. If they also have strong damping, the interference would be a little greater than that described, but the main imperfections of tuning are due to the resistance of the receiving station and not to the lack of purity of the wave from the sending station. The illustration shows that we cannot get very sharp resonance so long as we have to use a high resistance (the detectors) in the particular receiving circuit here employed. This difficulty is, however, considerably reduced by the use of coupled circuits at the sending and receiving stations, in the place of the simple condenser circuit of this computation.

In the next chapter some facts in regard to resonance with coupled circuits will be presented.

Simplified Form of Circuits. — In order to simplify the conditions somewhat, in the present experiments, instead of employing the wireless telegraph circuits with the antenna constituting

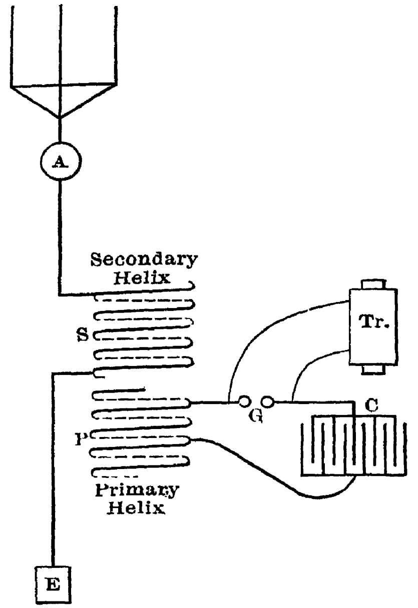

FIG. 151. Inductively coupled transmitting station.

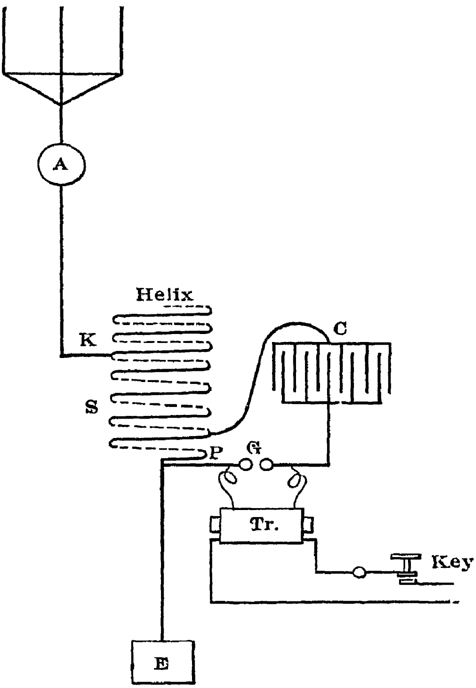

FIG. 152. Direct coupled transmitting station.

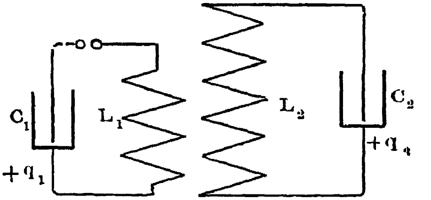

FIG. 153. Inductively coupled condenser circuits, with the antenna and ground of Fig. 151 replaced by a condenser.

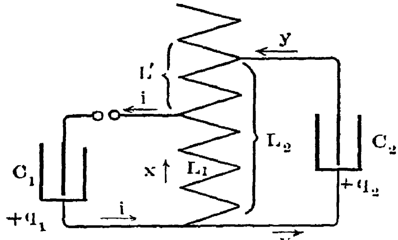

FIG. 154. Direct coupled condenser circuits.

the capacity of the secondary circuit (such an antenna being in the form of a capacity distributed along a wire also possessing inductance), this antenna, for the purposes of these experiments, is replaced by a condenser, so as to have a localized capacity in

In Fig. 155, which represents the inductively connected system, two condensers C_1 and C_2 are connected to two coils L_1 and L_2, which are inductively related but insulated from each other. The number of active turns of wire on each of the coils may be varied; L_2 is varied by the clip contacts, and L_1 is varied by a wheel contact that may be moved along the inner spiral by a rotation of the drum on which the inner spiral is wound.

Each of the condenser circuits is provided with a spark gap, so that either circuit, when connected to a step-up transformer, may be used as the discharge circuit. The other circuit may then be looked upon as a secondary circuit. When the spark gap of the secondary is opened too wide to permit the passage of a spark, or, what is the same thing, when the secondary is removed, the period of oscillation is the period of the primary alone. When, on the other hand, the secondary is left in place and the spark gap of the secondary is closed (compare Fig. 153), the oscillations of the discharge circuit C_1 L_1 induce oscillations in the secondary circuit C_2 L_2, and we have a periodic flow of current in both circuits. It is proposed to give an account of some measurements of the wave length produced in the circuits when uncoupled and then when coupled with each other, and to compare the measured values with values computed from certain useful formulas.

In the *Direct Coupled System*, represented in Fig. 156, which was also studied, the transformer of the inductive coupling is replaced by an auto-transformer; that is, the two condensers C_1 and C_2 are made to discharge through parts of the same coil. In this case, also, both the inductances L_1 and L_2 can be varied independently by the motion of the contacts W and S. Also, both the condenser circuits are provided with spark gaps, so that either circuit may be caused to oscillate alone or to constitute the discharge circuit in a connected system with closed secondary.

These two forms of circuits, Figs. 155 and 156, are derived from the ordinary wireless telegraph circuits by replacing the antenna and ground of the wireless telegraph station by the two coatings of a condenser respectively. The circuits in these simplified forms will yield results that will aid in understanding the actual wireless telegraph circuits, which are to be examined in subsequent chapters.

Dimensions of the Inductances. — The coils employed in the apparatus shown in Figs. 155 and 156 had the following dimensions:

convenient objects; for example, the backs of two chairs. The pendulum bobs may be any two small bodies of about the same weight—two heavy nails will do. At first make the lengths of the threads supporting the two pendulum bobs the same. Now leave one of the bobs at rest, pull back the other in a direction at right angles to the plane of the strings, and then release it. Note what happens. Try the effect of making the cross cord tighter or looser, and also the effect of making the two pendulums of unequal length.

The vibratory motion of the pendulums represents very well the electrical vibratory motion that takes place with the coupled condenser circuits.

Oscillograms of the Pendulum Motion. — In order to show graphically the nature of the pendulum motion, I have elaborated the pendulum apparatus a little, and taken a moving picture

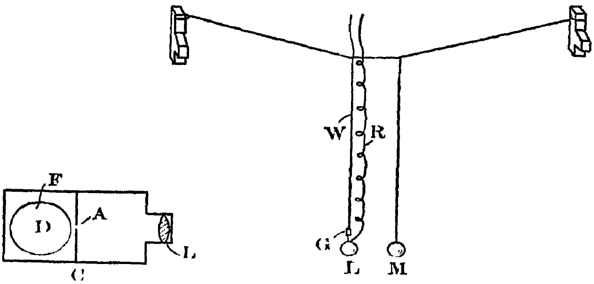

Fig. 158. Coupled pendulum with arrangement for photographing the motion.

(oscillogram) of the motion of each of the pendulum bobs. To do this, a camera was placed in the position shown at C in Fig. 158. At the back of the camera is a small horizontal slit A, and back of this slit is a sheet of bromide paper F carried by a rotating drum D. In order to have a bright object upon which to make the exposure, a small Nernst glower G was hung just above one of the pendulum bobs. This Nernst filament was put into an electric circuit by means of the small wire W, which also served as the suspension for the pendulum, and by means of the return wire R, which was carried up in such a manner as not to interfere with the freedom of motion of the pendulum. The current was started in the glower by heating it with a match while the current was on. As the pendulum swung, the image of the Nernst glower moved back and forth along the slit A. A small horizontally moving point of light thus entered the slit and fell upon the film. If now the sensitive

show the displacement of the bob plotted vertically, against time plotted horizontally.

The first curve P, of Fig. 159, was obtained by leaving the ball M initially at rest, and pulling aside and releasing ball L (Fig. 158). The motion here corresponds to the primary current in the coupled condenser circuits. The second curve S was obtained by leaving the ball L initially at rest and releasing M. This curve corresponds to the secondary current of the coupled condenser circuit. The two cords supporting L and M were of the same length in the case of these two experiments.

As another experiment, the two cords were both equally shortened, and the transverse supporting cord was loosened; the curves P' and S' were obtained for the motion of the ball L initially displaced (primary) and initially at rest (secondary) respectively.

The curves P and S or P' and S' represent very well the electrical vibratory motion of the coupled condenser circuits, if we think of the displacement of the bob in the two curves as representing the current in the primary and secondary circuits of the coupled-condenser oscillation.

How the Curves Show the Existence of Two Periods. — Each of the curves of Fig. 159 shows the existence of two periods, in the motion of the pendulum, by the presence of "beats." If two vibrations of different periods coexist in the same system, the slower of these vibrations will fall more and more behind the other in phase until the two vibrations become just opposite to each other and neutralize each other; then the slower vibration will again fall more and more behind till it is a whole vibration behind the faster, and the two vibrations will then add and intensify each other. This is what has happened in the experiment with the pendulums. The same thing happens with the electrical vibrations of the condenser circuits that are coupled together.

Theoretical Values of Wave Lengths in the Coupled Circuits. — Let us now return to the experiments with the condenser circuits. By the use of the wave meter we can pick out and measure each of the periods or the corresponding wave lengths of the connected system of condenser circuits. When this has been done, we shall find that the wave lengths obtained satisfy the following theoretical relations [1]:

[1] Lord Rayleigh, Theory of Sound; J. v. Geitler, Sitz. d. k. Akad. d. Wiss. z. Wien, February and October, 1905; B. Galitzine, Petersb. Ber., May and June, 1895; V. Bjerknes, Ann. der Physik, Vol. 55, p. 120, 1895; Oberbeck, Ann. der

TABLE XIII

INDUCTIVELY CONNECTED SYSTEM

Primary capacity .00432 microfarad.
Primary inductance varied.
Secondary capacity .00482.
Secondary inductance 24 turns outer coil, $L_2 = 6.60 \times 10^{-5}$ henry.
Wave length of secondary $\lambda_2 = 1060$ meters.

Turns Primary.	L_1 Primary Inductance. Henry.	M Henry.	τ^2
50	15.85×10^{-5}	6.52×10^{-5}	.412
45	13.9	6.14	.421
40	11.8	5.80	.430
35	10.0	5.12	.397
30	8.20	4.45	.360
25	6.50	3.56	.295
20	4.82	2.70	.228
15	3.15	1.95	.183
10	1.72	1.20	.128
5	.69	.47	.048
3	.32	.23	.0277

Turns Primary.	λ_1 Meters.	Calculated.		Observed.	
		λ_1' Meters.	λ_2' Meters.	λ_1' Meters.	λ_2' Meters.
50	1560	1740	727	1750	710
45	1460	1670	712	1650	685
40	1350	1567	686	1570	465
35	1230	1462	680	1480	660
30	1130	1390	660	1370	660
25	1000	1273	685	1280	660
20	870	1185	680	1185	630
15	700	1127	595	1125	565
10	510	1080	467	1090	460
5	300	1060	292	1040	285
3	210	1062	193	1075	210

The method of taking the observations is as follows: First, the condenser C_2 (= .00482 mf.) was connected in series with 24 turns of the outer coil (Fig. 155) and was provided with a spark gap. In this position, with the inner coil thrown out of circuit by disconnecting both plates of its condenser, the wave length λ_2 was found to be 1060 meters. Next, with the secondary condenser disconnected, the wave length of the primary (inner) circuit was determined with its condenser C_1 (= .00432 mf.) connected in series with 50 turns of the inner coil. This wave length λ_1 was 1560 meters. Next, with the primary left unaltered, the secondary was closed by attaching its condensers without spark gap to the 24 turns of the outer coil. This is the case of the closed second-

obtained both by measurement and by calculation. The observed and calculated results are plotted in the curves of Fig. 161. In this case also the agreement is fairly satisfactory.

These two experiments with the inductively connected system of circuits give an experimental verification of the formulas (1), (2), (3), (4) and (5), and serve to show how the wave lengths obtained with the connected system depend on the constants of

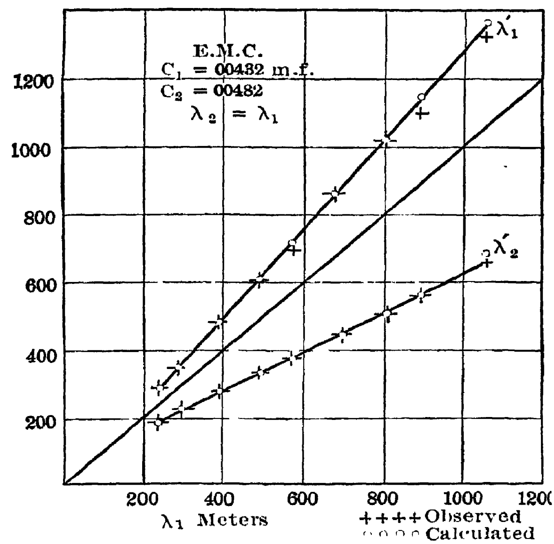

FIG. 161. Curves of wave lengths obtained with inductively coupled condenser circuits having individually the same period.

the two circuits. We shall return to this subject after giving briefly the results of an experiment with the direct coupled system of circuits.

Experiment with the Direct Coupled Circuit. — C_2 = .00178 **Microfarads,** L_2 = 25.5 **Turns** = 6.7 × 10 $^{-5}$ **Henrys,** λ_2 = 645 **Meters.** — The apparatus for this experiment with the direct circuit is shown in Fig. 156. The steps of the experiment are similar to those with the other system of circuits. The observed and calculated values of the wave lengths in the compound oscillating system are plotted in Fig. 162. The formulas of calculation are the formulas (1) and (2), and the agreement between the observed and calculated results (crosses and circles) is seen to be satisfactory.

When τ is equal to unity *the coupling is said to be perfect* and the equations (1) and (2) become

$$\lambda_1' = \sqrt{\lambda_1^2 + \lambda_2^2};$$

and

$$\lambda_2' = 0.$$

That is to say, the oscillation, as shown also by method I, becomes single-valued.

The case of perfect coupling was not observed in the experiments with the *inductively coupled system*, because for perfect coupling the primary and secondary coils must have the same number of windings and the two coils must be so close together as to be practically coincident,—conditions that could not be realized with the inductive coupling.

Close Coupling and Loose Coupling. — One of the most interesting facts derivable from an examination of the equations (1) and (2), which are verified by the experiments, is the influence of the coefficient of coupling (τ) on the wave lengths produced by the coupled circuits. In general, two wave lengths are obtained when a coupled system of circuits is set into oscillation. This duplicity of the wave length is often an inconvenience in wireless telegraphy, because, to avoid interference when a neighbor is sending a message we do not wish to hear, it is necessary to tune to avoid, not one undesired wave, but two.

The influence of the coefficient of coupling on the wave length is very easy to investigate in case the primary and secondary of the coupled system are attuned to the same wave length λ, as they generally are in practice. In this case, the formulas for the compound wave lengths λ_1' and λ_2' become the simple forms of equation (4) and (5); namely,

$$(\lambda_1')^2 = \lambda^2 (1 + \tau), \tag{4}$$

and

$$(\lambda_2')^2 = \lambda^2 (1 - \tau). \tag{5}$$

Dividing each of these equations by λ^2, and extracting the square root, we have,

$$\frac{\lambda_1'}{\lambda} = \sqrt{1 + \tau} \tag{7}$$

$$\frac{\lambda_2'}{\lambda} = \sqrt{1 - \tau} \tag{8}$$

Now, putting in various values of τ = (.1, .2, .3, etc., up to 1.0), we obtain the relative values of λ_1' and λ_2', shown in the curves of Fig. 164.

CHAPTER XXII

TUNING THE SENDING STATION

HAVING investigated, in the preceding chapter, the conditions of resonance and the manner of vibration of two condenser circuits connected together, it is proposed now to consider the actual wireless telegraph sending circuits. For this purpose let us examine the method of adjusting the direct coupled or the inductively coupled sending station to resonance. A diagram of a direct coupled sending station is shown in Fig. 165. The condenser *C*, repeatedly and periodically charged from a transformer *Tr*, discharges through a spark gap *G* and a few turns *P* of a "helix." The oscillations in this circuit act inductively and produce oscillations in the antenna circuit consisting of the antenna, the coils *S* of the helix, and the ground *E*. A maximum effect is produced when these two circuits are properly adjusted to each other. A photograph, Fig. 166, is given to show the construction of the sending helix (right) and a method of inclosing the spark gap for reducing the noise of the spark.

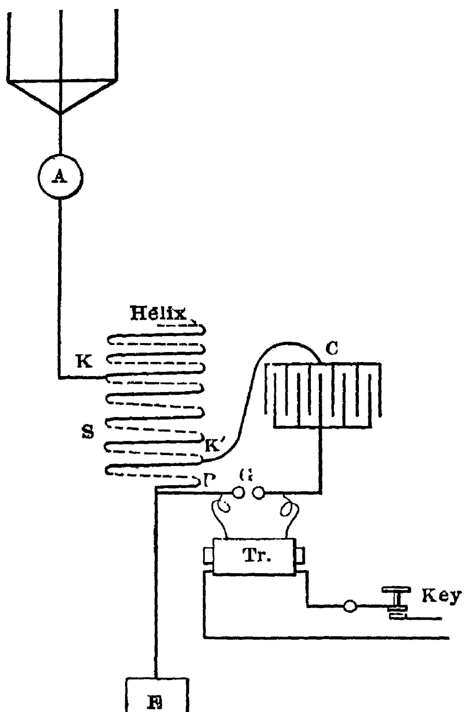

FIG. 165. Direct coupled transmitting station.

A diagram of the inductively coupled sending circuit is shown in Fig. 167. Here the primary and secondary inductances are parts *P* and *S* of two separate helices. These two helices may be one above the other, as represented in the diagram, or may be one

meter *WM* up near the helix. The lower end of this helix is connected through a spark gap to the ground. The secondary of the station's transformer is connected about the spark gap. The

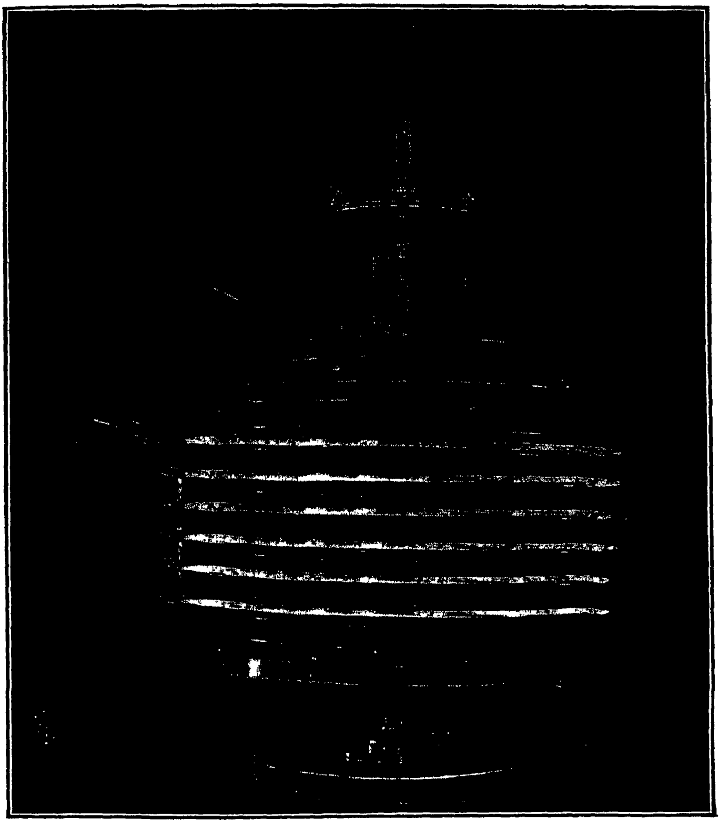

FIG. 168. Showing construction of the helices of an inductively coupled transmitting station.

antenna is connected by means of a clip contact *K* to some particular number of turns of the helix. The transformer is set into operation so as to produce a spark at the gap.[1] This sets up oscillations in the antenna circuit, and the wave meter is adjusted to resonance with these oscillations. The wave length is read, and this reading

[1] In this case, where the spark gap is in the antenna circuit, there is a tendency for the spark to go over into an arc and not produce good oscillations. This may be obviated by playing a small blast of air on the spark.

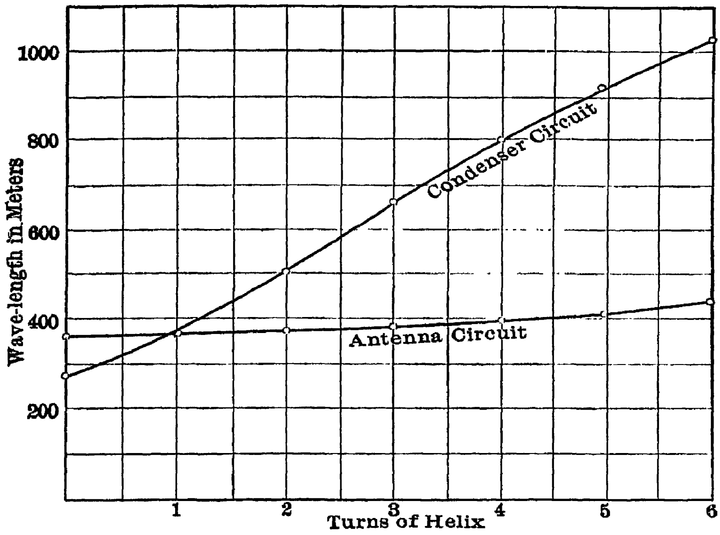

FIG. 170. Curves showing wave lengths of antenna circuit and condenser circuit with different numbers of turns of the helix.

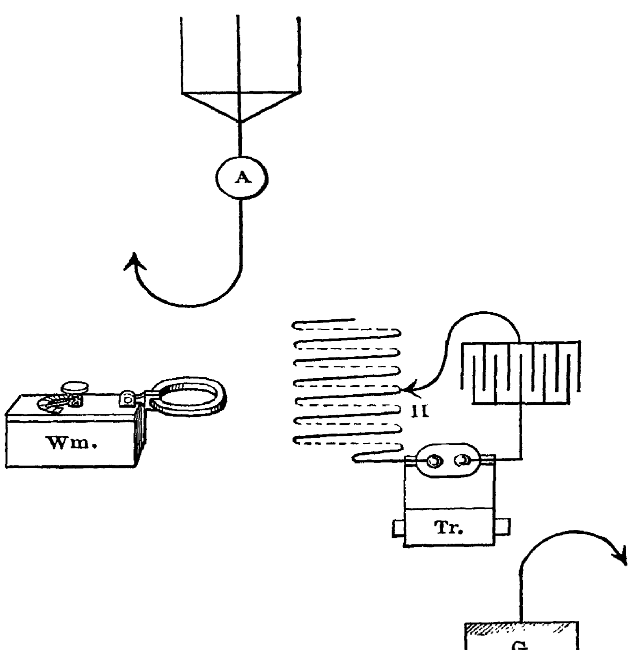

FIG. 171. Method of measuring wave length of the condenser circuit.

Adjustment of Direct Coupled Sending Station to Resonance with the Aid of a Hot-wire Ammeter. — Another method of adjusting the condenser circuit and the antenna circuit to resonance makes use of a hot-wire ammeter, inserted in the antenna circuit as represented at A, Fig. 165. This instrument contains a fine wire through which the oscillations pass, producing heat. The heated wire expands, and by means of a delicate gearing attachment, the sagging of the expanding wire acts upon a hand passing over a dial. The movement of the hand over the dial is thus an indication of the amount of current passing through the sensitive wire. The instrument may be calibrated directly in amperes, but this calibration (chiefly on account of the shunts that have to be employed) is without much absolute value, when the hot-wire ammeter is used with the very rapid oscillations of wireless telegraphy. Nevertheless, a maximum deflection of the instrument indicates a maximum of current in the antenna, and this is all that is required of the hot-wire ammeter in order to decide when the antenna and condenser circuits are in resonance.

Instead of inserting the hot-wire ammeter in the antenna above the helix, it may just as well be placed in the lead from the helix to the ground. In either case oscillations in the antenna circuit pass through the instrument.

To tune up a station with a hot-wire ammeter, let the station be coupled up as shown in Fig. 165. Set the transformer in action, and read the hot-wire ammeter. Now keeping the spark gap constant, and leaving the antenna clip K unchanged, move the clip K' of the condenser circuit to a different number of turns of the helix, and again read the current. Make a table containing the number of turns of helix in primary circuit and corresponding hot-wire ammeter readings. Then plot a curve of readings against turns in the form shown in Fig. 173. From this figure it is seen that the maximum reading of the ammeter was obtained when the primary was discharging through 1.3 turns of the helix. This is, therefore, the adjustment that must be given to the primary inductance in order to bring the condenser circuit into resonance with the antenna circuit, for the fixed value of the secondary inductance employed throughout the adjustment.

Since the readings of the hot-wire ammeter depend on the values of the mean square current through it, one can, by a process like that described, find out just what conditions of the two circuits give the greatest mean square current in the antenna, and if

the primary and secondary helices brings the two resultant wave lengths produced by the station closer together, and gives a sharper wave system than that obtained with a large coefficient of coupling. The coefficient of coupling of the direct coupled system also may be varied, for example, by introducing more or less inductance (not mutual) in one of the circuits.

The question as to the best coefficient of coupling to employ at the transmitting station is difficult to decide. The question is complicated by the conditions that exist at the receiving station as well as at the sending station. I shall therefore defer a consideration of this question until after a discussion of the resonant relations at the receiving station.

The Detuning of Coupled Circuits. — We have shown in the preceding paragraphs how the condenser circuit and the antenna circuit may be adjusted to resonance. This gives in the coupled system a maximum flow of current and a maximum radiation of energy from the antenna. The energy radiated is, however, in the form of two waves of different wave lengths. Suppose this doubly periodic wave to be received by a receiving circuit. Can we not tune the receiving circuit either to the one or to the other of the received wave lengths? And would it not be preferable to adjust the transmitting condenser circuit to a little longer or a little shorter wave than the transmitting antenna circuit in order to strengthen the longer or the shorter wave of the coupled system at the expense of the other wave which is not to be used at the receiving circuit? Professor M. Wien [1] shows that a small advantage (in some cases as great as 30%) may be derived from a process of this kind provided the condenser circuit and the antenna circuit are differently damped. In his experiments Wien used a simple, low-resistance receiving circuit, and I am unable to say how great would be the advantage in a similar *detuning* operation, when the coupled receiving circuits and the high-resistance detectors of actual practice are used at the receiving apparatus. In my own experiments I have never detected any appreciable advantage in detuning an actual sending station.

Possible Existence of Three Wave Lengths in a Coupled System. — With the condenser circuit and the antenna circuit attuned to the same independent wave length, as in the case of our wave metrical illustration on page 248, there is the possibility of the

[1] Annalen der Physik, Vol. 25, p. 1, 1908.

CHAPTER XXIII

SOME RECENT METHODS OF EXCITING ELECTRIC WAVES THE SINGING ARC, THE SINGING SPARK, AND THE QUENCHED SPARK

Thus far in this account, practically only one method of producing oscillations at the sending station has been described; namely, the method making use of the spark discharge of a condenser which has been charged from an alternating current transformer or an induction coil. Electric waves produced in this way occur in discrete trains.

Recently several new methods of exciting the oscillations have come into use. We shall begin the discussion of these newer methods by describing the " singing arc," which is a wide departure from the ordinary spark discharge. The singing arc operates on a direct current source, produces a practically continuous sequence of waves, and has met with application, not only to wireless telegraphy, but also to wireless telephony. The history of the singing arc may be traced back more or less connectedly to an early experiment by Elihu Thomson.

Elihu Thomson's Continuous Current Spark. — In 1892 Professor Elihu Thomson [1] found that electric oscillations could be produced from a 500-volt direct current source by connecting the source through a resistance with a spark gap which was shunted by a condenser and inductance. This form of circuit is represented in Fig. 174. A source of direct electromotive force of 500 volts is shown at E. This is connected in series with a resistance R and a spark gap. In parallel with the gap a condenser C and a self-inductance L are shunted. Under these conditions electric oscillations were found to be present in the condenser circuit. In the effort to intensify and steady the effects Professor Thomson used a blast of air or a magnet to blow out the spark. This apparatus of Professor Thomson with some modifications and improvements has been reverted to in some of the recent developments of wireless telegraphy and telephony.

[1] U. S. Patent, No. 500,630, July 4, 1892.

an inductance S. With proper adjustments of the various parts of the circuit the arc emits a musical sound which in Duddell's experiments could be plainly heard to a distance of several meters. The pitch of the note can be varied by varying the capacity C or the inductance S. The experiment is highly interesting when one varies the capacity C by means of a set of keys and thereby produces a succession of notes of different pitches.

In addition to the evidence afforded by the emission of musical sounds, the shunt circuit comprising the condenser C, the inductance L and the arc A, may be shown also by its inductive action on a neighboring circuit to be traversed by a pulsating or oscillating current. We have thus a pulsating or oscillating current produced from a direct-current source.

Why the Arc Gives Rise to Pulsating Currents. — The explanation of the production of oscillatory currents and audible sounds by the arc shunted with a condenser has been the subject of a considerable amount of theoretical and experimental investigation.[1] Duddell's original account of the phenomenon contains a simple explanation, which is substantially as follows:

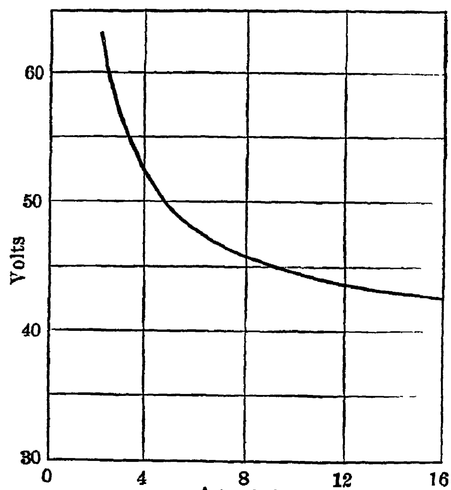

FIG. 177. Volt-ampere characteristic of carbon arc.

The electric arc between carbon terminals has a falling volt-ampere characteristic like that shown in Fig. 177. With an increase of current through the arc the voltage between the arc terminals decreases. For this reason, when the arc is connected in series with a source of voltage and is "struck" by bringing the terminals together and then separating them, the current through the arc tends to increase to a very large value, and must be restrained by a suitable resistance R in circuit with the arc (see Fig. 176).

Suppose, now, that when the arc is quietly burning, a condenser C and inductance S are together connected about the arc. The

[1] For a theoretical treatment of this subject the mathematical reader is referred to an article by H. Th. Simon, Physikalische Zeitschrift, Vol. 7, p. 433, 1906.

primarily in placing the arc in an atmosphere of *coal gas or hydrogen*, and in employing for the arc one terminal of carbon (−) and the other terminal of a water-cooled cylinder of copper (+) (cf. Fig. 178). For the purpose of effecting the cooling of the copper electrode, it was made hollow, and through it a stream of water was circulated. Water was also circulated through a worm within the jacket inclosing the coal gas or hydrogen about the arc, so as to prevent undue heating of this jacket. To enhance the strength

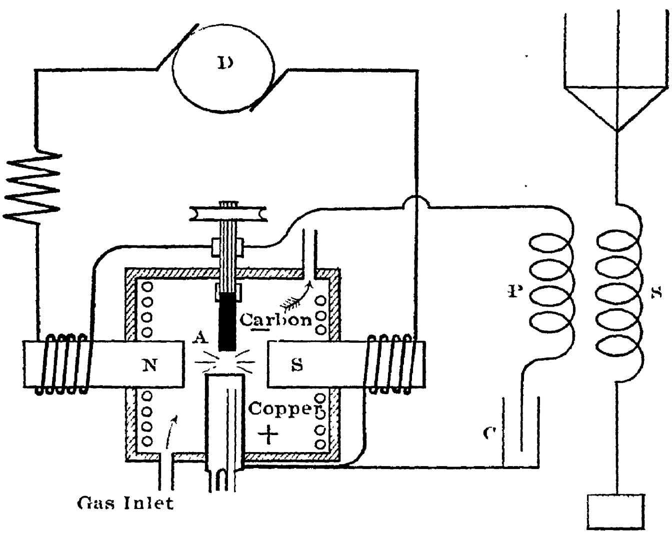

FIG. 178. Mr. Poulsen's singing-arc generator of electric waves.

and the frequency of the oscillations, the poles of a powerful electromagnet *NS* are inserted, gas-tight, into the chamber, and placed so as to give a magnetic field transverse to the arc. The carbon terminal of the arc is slowly rotated by a clockwork or electric motor. This is to prevent the formation by the arc of inequalities in the surface of the carbon electrode. When all of these precautions indicated by Poulsen are taken, the oscillations may be given a frequency as high as a million or more per second,[1] which brings them well within the range useful for wireless telegraphy and telephony.

The source of current is a direct current generator *D*, giving

[1] By the use of an arc having a water-cooled copper cathode and a silver-point anode, N. Stschodro (Ann. d. Phys. Vol. 27, p. 225, 1908), has obtained more than 300,000,000 oscillations per second, and has performed Hertz's mirror experiment with the electric waves so produced.

frequency can be obtained, even with the arc in air. The surrounding of the arc with an atmosphere of hydrogen permits these high-frequency oscillations to be obtained also with a large current (10 to 12 amperes) through the arc, which is a valuable asset for the sustenance of energetic oscillations.

Instead of employing an atmosphere of hydrogen about the arc, ordinary coal gas, such as is used in illumination, produces also very good results.

One method of feeding the gas into the chamber is to lead it in continuously by a rubber tube connected with the gas jet of the illuminating system. The gas, after passing through the chamber about the arc, is conducted away by a rubber tube leading to the outside of the building, or else it is led to a gas burner and ignited to prevent it from escaping unconsumed into the room.

The Use of Other Hydrocarbon Gases and the Use of Steam About the Arc. — Instead of coal gas or hydrogen, almost any other gaseous hydrocarbon may also be employed with the arc to enhance the energy and improve the constancy of the high-frequency oscillations. For example, the combustion products of an alcohol flame will produce effects in a degree similar to effects with the coal gas. These combustion products may be supplied to the arc by means of a small alcohol lamp placed beneath the arc, as is shown in Fig. 180.

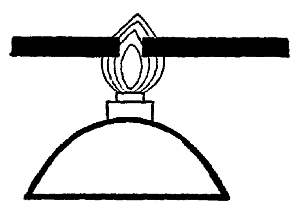

FIG. 180. Carbon arc in alcohol flame.

Similar beneficial effects upon the oscillations are produced by the gases formed by the volatilization of a liquid hydrocarbon, such as turpentine, pentane, amyl alcohol, etc. In this case the liquid hydrocarbon is allowed to fall drop by drop into a cup-shaped depression in one electrode, where it is volatilized and surrounds the arc with an atmosphere of gas.

Dr. Lee DeForest [1] has suggested steam as an atmosphere for the arc, and has shown several methods of supplying steam to the arc. One of these methods is depicted in Fig. 181 taken from DeForest's United States patent specifications.

Use of Several Arcs in Series. — To obviate the necessity of the magnetic field and the coal-gas atmosphere, as used with the Poulsen arc, the Telefunken Company of Germany employs several arcs in series, thus obtaining a high effective voltage. Only a

[1] U. S. Patent, No. 850,917, issued April 23, 1907.

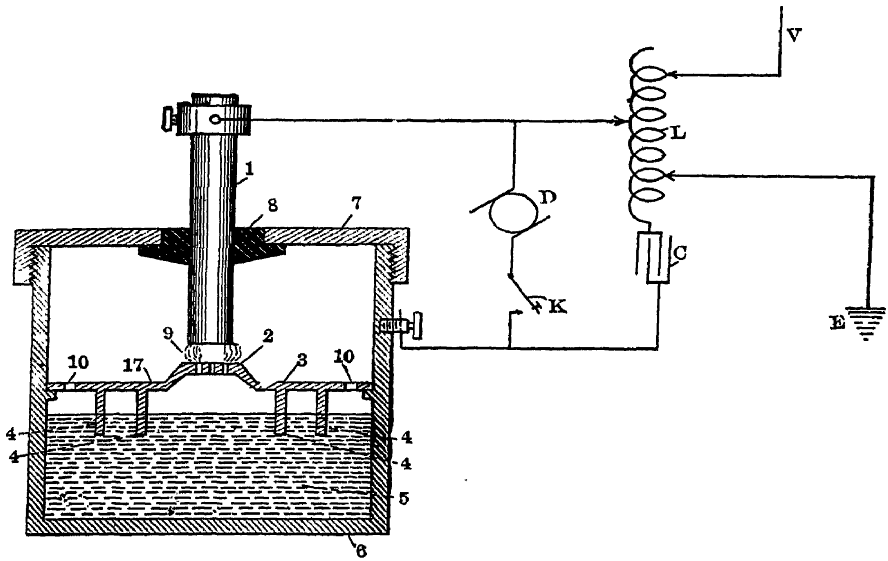

FIG. 181. DeForest's arc in steam.

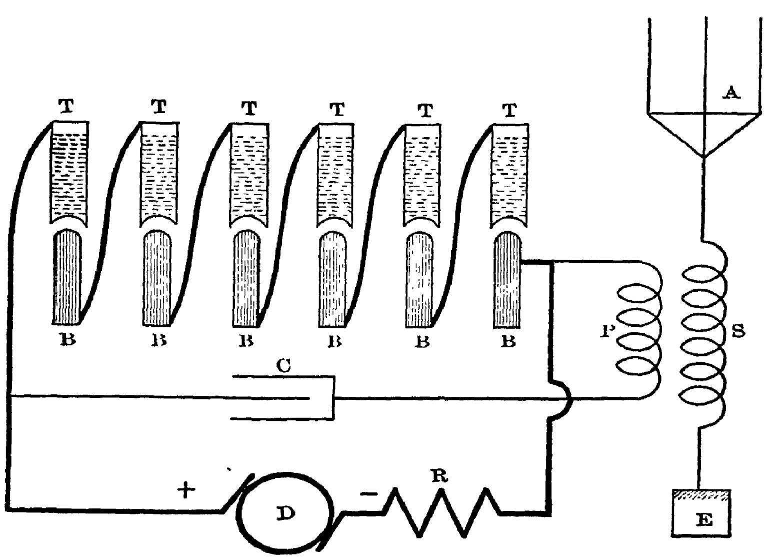

FIG. 182. Telefunken arcs in series.

Instead of having the interrupter or detuning vibrator at the sending station, it may be used at the receiving station, as has been proposed by Poulsen.[1] A diagram of a circuit in which this is done, taken from Mr. Poulsen's United States patent specification, is shown in Fig. 183. The receiving antenna circuit *a* is inductively connected with the condenser circuit *b*, *c*, *d*. In shunt about the condenser *d* is a detector *s* with its accessories. A vibrating interrupter at *f* is adapted to connect another condenser *k* periodically in parallel with the condenser *c*. When the contact is interrupted at *f*, assuming that the oscillation circuit is tuned to resonance under these circumstances, intense oscillations will appear in this circuit, and by means of the detector at *s*, which rectifies the oscillations, an integral current will pass through the telephone. If now the contact at *f* is closed, the circuit is thrown out of resonance, oscillations in the circuit *b*, *c*, *d* cease, and the current in the telephone ceases. When the contact at *f* is again opened, another integral current passes through the telephone, which in this way is made to respond with a sound of pitch determined by the frequency of the interrupter.[2]

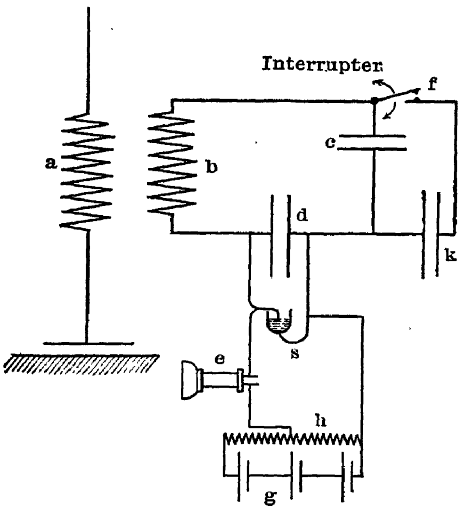

FIG. 183. Receiving circuit for persistent waves (Poulsen).

In order to obviate the necessity of these interrupter devices at the sending or receiving circuit, an Einthoven galvanometer at the receiving station may be used instead of the receiving telephone. Einthoven's instrument will respond to the uninterrupted train of waves and possesses a sensitiveness even greater than the telephone receiver. The deflections of this galvanometer may be photographically recorded. Although this instrument, with the necessary moving film for taking the photographic record of the message, is not quite so simple to install or to operate as the circuit

[1] U. S. Patent, No. 897, 779, applied for March 6, 1907, issued Sept. 1, 1908.

[2] The explanation given by Mr. Poulsen in his patent specification is inconsistent with the explanation here given.

that the interference difficulties, even with undamped waves, are still considerable.

The main advantage in the singing-arc method of excitation arises in the applicability to *wireless telephony* of this method of producing electric oscillations. Wireless telephony is briefly considered in a subsequent chapter.

As a continuation of the discussion of novel methods of producing oscillations, we shall next describe the Lepel arc and the quenched spark.

The Lepel Arc. — In a German Patent, No. 24,757, filed Aug. 20, 1907, Baron von Lepel has described a very simple and efficient form of discharge gap which is capable of operating on either a direct or an alternating-current source. It consists simply of two circular discs of copper with a thin sheet of paper between them. The discharge occurs between the discs and through the paper. A small perforation made near the center of the paper affords a suitable starting place for the discharge. As the discharge continues, the paper is gradually burned away from the center outwards. This burning away takes place in an atmosphere deficient in oxygen, and consequently requires several hours to use up all the paper. A circular groove cut near the outside edge of the adjacent faces of the copper plates prevents the arc from getting to the outer edge of the discs and there being exposed to the air. The essential feature of the Lepel gap is that the spark or arc shall be very short and shall occur in the space which is deficient in oxygen. The presence of the products of combustion of the paper enhances the efficiency of the arc. The arc will operate on a direct current source, and gives discrete trains of oscillations of which the pitch may be made very high and may be regulated by regulating the condenser about the gap and the rheostat placed in the leads to the current supply.

The series of discharges obtained from the direct-current supply occurs in a manner resembling the occurrence of the series of discharges obtained by Elihu Thomson with his singing spark, as described on page 253. In addition each discharge is rapidly quenched and gives the quenched-spark effect described under the next heading.

The discs of the Lepel arc are 3 to 5 inches in diameter, and, for rapid conduction away of the heat generated, are made of copper or silver, which have high conductivity for heat. The discs may also be made hollow, and are then cooled by the admission of

corresponding electrical case. P and S represent the current in the primary and secondary oscillating circuit having in the primary an ordinary spark gap. P' and S' represent the current in the primary and secondary of a system having a quenched spark in the primary. The spark is quenched when the energy in the primary attains its first minimum. If this spark does not recover its conductivity again, the secondary oscillation continues with its own free period and damping as represented in S'.

Now it has been shown that a very short spark kept well cooled has exactly this characteristic of rapidly extinguishing after a

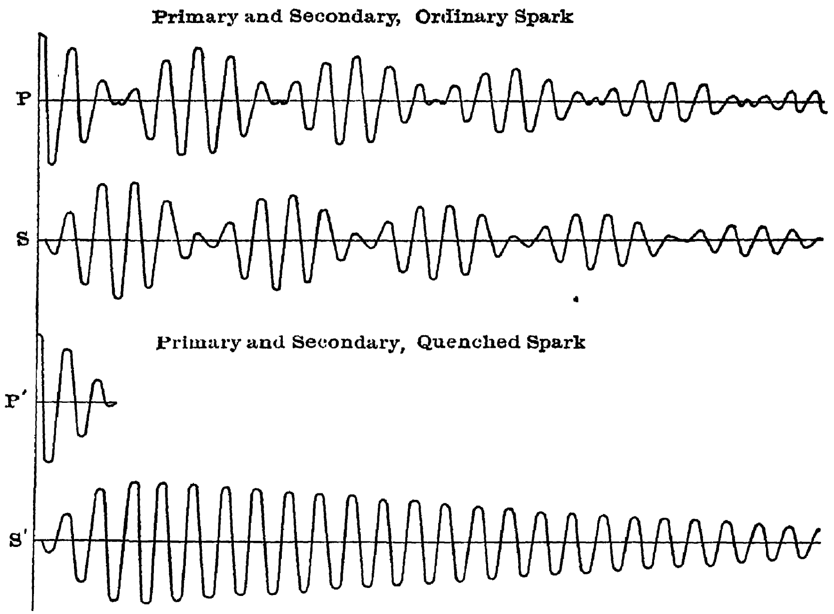

FIG. 184. Curves showing oscillations with ordinary spark and with quenched spark.

few oscillations, as is represented by the curve P'. A method of attaining a similar result with a comparatively large amount of power consists in using several gaps of the Lepel type in series.

This has been done by the Telefunken Company in Germany with marked success. A diagram of the quenched spark, comprised of several minute gaps in series between metal discs, is shown in Fig. 185. The face of one of these discs, which are of copper, is shown in the upper part of the figure. The lower part of the figure shows a section of a pile of these discs, placed so as to give several of the gaps in series. Between each pair of the discs is a

surfaces. One gap will carry efficiently not more than 4 amperes. The oscillations occur in a practically continuous train and are suitable for wireless telephony. To give a tone to the discharge, so as to adapt it to wireless telegraphy with a rectifier and telephone as receiver, one of the discs may be segmented.

Some Facts in Regard to the Quenched Spark. — Recurring to the curves of Fig. 184, it will be seen wherein consists the advantage of a properly quenched spark; namely, the spark is active only long enough to allow the oscillations of the antenna circuit to build up to a maximum of intensity. The number of oscillations of the primary requisite to attain this is the fewer the closer the coupling between primary and secondary. The intensity of the secondary is a maximum when the current of the primary is a minimum. If the spark completely loses its conductivity at this point, the subsequent oscillations of the secondary induce an electromotive force in the primary, but if no current is established in the primary, no energy is thereby consumed, and all of the energy, which is now stored in the secondary circuit, will stay there until radiated.

If, on the other hand, the primary spark does not completely lose its conductivity at its minimum, the e.m.f. impressed back on the primary by the oscillations in the secondary will reëstablish current in the primary. This current in the primary, flowing as it does repeatedly across the spark gap, heats it, and dissipates a considerable part of the energy of the system as heat in the gap. This recommunication of energy to the primary is worse than useless because in addition to dissipating energy, it is active also in burning away the spark gap and in severely straining and heating the transmitting condensers.

In addition to this loss of energy and the destructive strain on the apparatus, the double periodicity of the vibration, with the use of the unquenched spark, is a hindrance to discriminating tuning of the receiving station.

The quenched spark is, therefore, economical in transmitting energy, and is favorable to sharp tuning; and, by obviating a useless dissipation of energy in the primary circuit, it also materially contributes to the life of the transmitting apparatus.

What are the characteristics of a spark gap in order that it should give a quenched spark? After the energy has left the primary circuit, the gap should very rapidly recover its high resistance, so that oscillations will not again be set up in the primary by the reaction of the secondary. This the author found to be

CHAPTER XXIV

RESONANCE OF RECEIVING CIRCUITS. THE POSSIBILITY OF PREVENTING INTERFERENCE

How does the current induced in a receiving antenna depend upon the height of the receiving antenna? How much is the strength of this current modified by tuning the antenna ? In a coupled receiving circuit what resonant relations exist between the two parts of the coupled system ? How sharp is the tuning at the receiving station, and to what extent can interference be prevented ?

It is proposed in this chapter to present a brief examination of these questions.[1] For this purpose some experiments are described.

DEPENDENCE OF RECEIVED CURRENT ON HEIGHT OF RECEIVING ANTENNA

In an investigation to ascertain the dependence of received current on the height of receiving antenna, a direct coupled transmitter, like that illustrated in Figs. 152 and 165 was used to produce the electric waves. The two circuits of the transmitting station were adjusted to resonance with each other by the hot-wire ammeter method of Chapter XXII. The dimensions of the transmitting circuits were as follows: The secondary part S of the helix consisted of 5 turns of wire .208 cm. in diameter, wound in a spiral 46 cm. in diameter, with a pitch of 5.08 cm. The inductance of this part of the helix was 1.56×10^{-5} henrys. The primary part P of the helix consisted of 1.2 turns and had an inductance of $.151 \times 10^{-5}$ henrys. The condenser was made up of sheets of copper separated by miconite plates. The antenna, with dimensions marked, is shown in Fig. 186. The station sent out two waves, — one of wave length 153 meters and the other of wave length 129 meters.

For the purpose of determining what relative currents are

[1] G. W. Pierce: Physical Review, Vol. 19, p. 196, 1904; Vol. 20, p. 220, 1905; Vol. 21, p. 367, 1905; Vol. 22, p. 159, 1906.

The variable inductance used for tuning the circuit consisted of 51 turns of wire, .208 cm. in diameter, wound in a spiral on a vulcanite drum. Variations of inductance were made by turning the drum, and thereby causing a wheel-contact to move along the spiral. The inductance of the whole coil was 16.5×10^{-5} henrys, and the inductance of any fraction of the coil was accurately known.

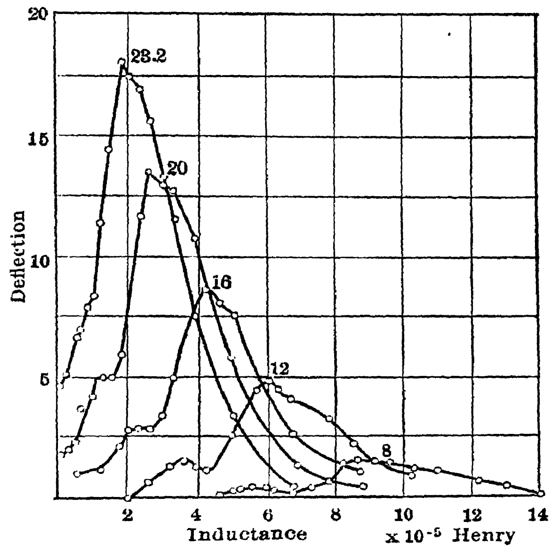

FIG. 188. Resonance curves with circuit of form of Fig. 187.

The results of a set of measurements are given in the curves of Fig. 188. The first curve, marked 23.2 at its vertex, was taken with a vertical receiving antenna 23.2 meters long (measured from the junction with the tuning coil). The different points on this curve were obtained as deflections of the dynamometer for different values of the inductance of the tuning coil. When the length of the receiving antenna was changed from 23.2 meters to 20 meters, the curve marked 20 at its vertex was obtained. In the same way the curves marked 16, 12 and 8 were obtained for lengths of antenna 16, 12 and 8 meters respectively.

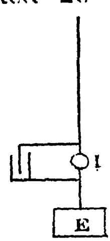

FIG. 189. Circuit for tuning with shunt capacity.

Before discussing the results of this experiment I will present data obtained with a different form of receiving circuit.

Similar Experiments with Shunt-Capacity Method of Tuning. — A diagram of this receiving circuit is shown in Fig. 189. An adjustable air condenser of known calibration in terms of capacity was placed in shunt to the receiving instrument, *I*, and by its use tuning was effected. Different lengths of receiving antenna were employed and the resonance curves of deflections against capacity were plotted. These are given

obtained with the series-inductance method. The deflection at resonance for the two different methods of tuning, for different heights of antenna, are plotted in Fig. 192. The lower curve A was obtained with the inductance method of tuning; the curve B,

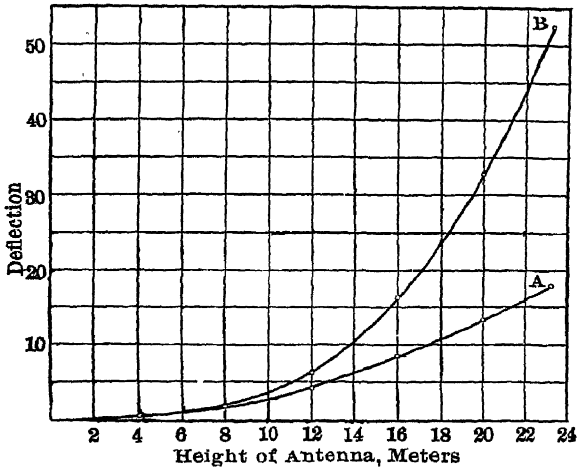

FIG. 192. Deflection as a function of the height of antenna. A, circuit tuned with series inductance; B, tuned with shunt capacity.

with the shunt-capacity method. It is seen that the shunt-capacity method of tuning gives larger values. In comparing these results numerically it should be remembered that the deflections of the instrument are proportional to the square of the current received.

Relation of Received Current to Height of Receiving Antenna. — Coming now to the more important question as to the relation of received current to height of receiving antenna for each of the methods of tuning, we get the interesting result that the law is entirely different for the two different methods.

In order to make the relation apparent, the scale of the deflections was changed by a constant multiplier so as to make the deflection at 23.2 meters unity. The simplified relative deflections thus obtained, together with the square roots and the fourth roots of these deflections are plotted in Figs. 193 and 194. It is seen that in the series-inductance case (Fig. 193) the square-roots of the deflections lie on a straight line, while in the shunt-capacity case (Fig. 194) it is the fourth roots of the deflections that lie on a straight line.

Remembering that the deflections of the instrument are pro-

as they should for an exact proportion. The reason of this departure from proportionality in the case of Law II may be found in the fact that the lengths of antenna were measured from the instrument to the top of the antenna. This leaves out of account the part of the antenna between the instrument and the ground, which amounted to 2 meters. This was also exposed to the action of the waves, and should perhaps be added to the height; this would make Law II almost an exact statement of the experimental result.

It is entirely possible that the relations I and II here stated may fail of verification when tested with greater heights of antenna. In the meanwhile the relations may be taken as fair approximations to the truth.

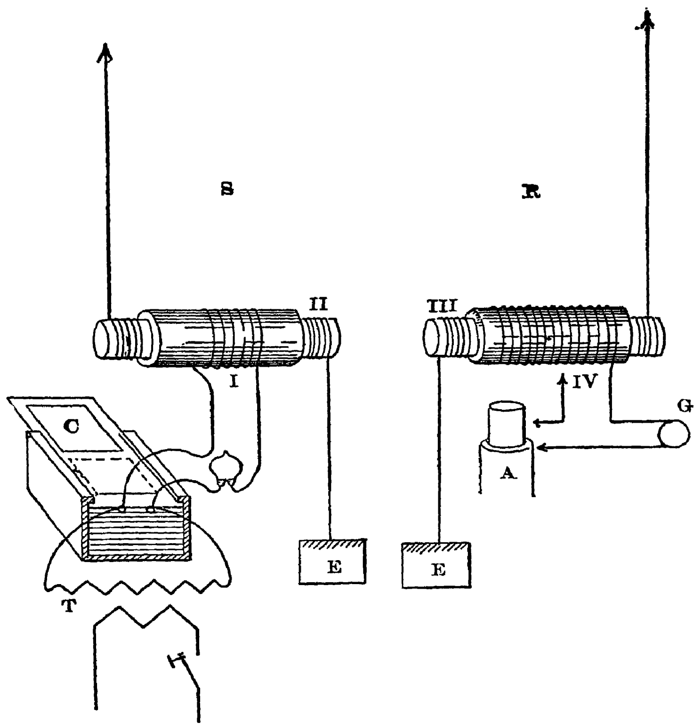

FIG. 195. Transmitting and receiving circuits for resonance experiments.

RESONANCE IN INDUCTIVELY COUPLED RECEIVING CIRCUIT

In the present experiments the inductively coupled type of circuits was employed at both the sending and the receiving stations. These circuits are shown in Fig. 195. It is seen that the

nating electric light circuit. The secondary of the transformer was connected to the condenser C, Fig. 195. The switch in the primary was closed and opened automatically by a clockwork, so that the signals were sent every 35 seconds, without the aid of an assistant. Each signal lasted for 5 seconds, which was a little greater than the time required for reading the receiving instrument.

Receiving Instrument. — The receiving instrument, shown at G, Fig. 195, was again the high-frequency dynamometer (described on p. 113), with a resistance of 1.33 ohms. Such an instrument of low resistance does not materially modify the resonance conditions, so that the results obtained are the results for the circuits themselves. When these circuits are employed with the commercial detectors of high resistance, it is necessary to ascertain how far the resonance relations are modified by the detector. At present, however, we are concerned primarily with the resonant behavior of the circuits themselves.

Harmonic Oscillation. — The following experiment shows the possibility of harmonic resonance of the inductively coupled

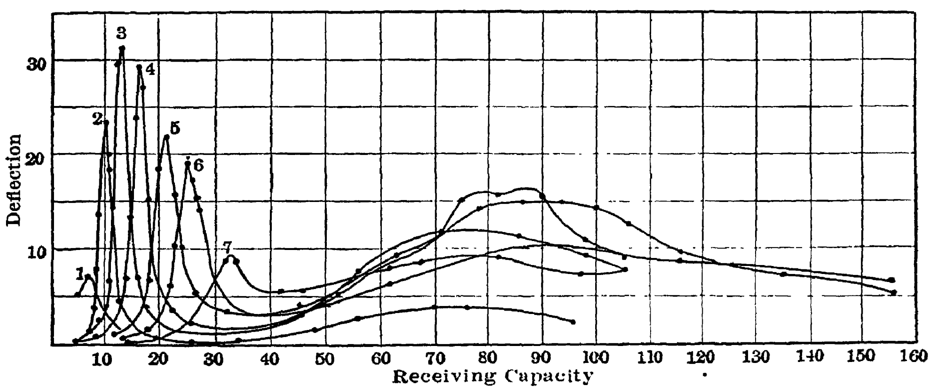

FIG. 196. Resonance curves obtained by taking readings of the dynamometer with various adjustments of the sending and receiving condensers.

sending and receiving circuits. With the sending and receiving antennæ circuits of identical dimensions, different values were given to the capacity of the sending station, and resonance curves were taken by variations of the receiving capacity. The curves of Fig. 196 were obtained. Curves 1, 2, 3, . . . 7 were with 1, 2, 3, . . . 7 plates of condenser at the sending station. It is

change in the antenna circuit. The reason is apparent. The 15 plates set the antenna vibrating with its fundamental period, while the 3 plates set the antenna vibrating as a first odd harmonic. The plates of the sending condenser were not all equal, so we must look to the receiving apparatus for a verification of this statement. This verification is evident from the optimum values of the resonant receiving capacity; namely, approximately 108 and 12, which are in the ratio of 9 to 1. These capacities being in the ratio of 9 to 1, the corresponding periods, which are proportional to the square root of the capacities, are in the ratio of 3 to 1, which is the ratio of fundamental to first odd harmonic.

This evidence of the possibility of a harmonic excitation of the sending antenna, and the harmonic response of the receiving antenna, shows the interesting analogy of the electrical apparatus to such acoustic apparatus as a closed organ pipe.

This experiment was performed with the receiving antenna circuit an exact duplicate of the sending antenna. For the purpose of obtaining information somewhat more general, it is proposed next to show some experiments with variations of the length of the receiving antenna, and to study the resulting effects on resonance.

Resonance Curves with Variation of the Length of Receiving Antenna. — The inductively coupled transmitting station *S* of Fig. 195 was employed to produce the waves. The sending antenna used was the four-wire antenna 15.8 meters long of Fig. 186. The sending condenser circuit was carefully adjusted to resonance with the antenna. The conditions at the sending station were kept constant.

At the receiving station, which was also inductively coupled (cf. *R*, Fig. 195), the coils of the inductive coupling were kept constant. The problem was to set up at the receiving station various heights of antenna, make various adjustments of the condenser in the side circuit and take readings of deflections of the dynamometer which is in the side circuit.

We have arriving at the receiving station waves of constant period and approximately constant intensity, and we are to seek the conditions under which the receiving instrument shows the largest readings. The variables are the height of the receiving antenna and the capacity of the air condenser, which is in the side circuit at the receiving station.

The receiving antenna of four wires was started at a height of 23.8 meters, measured from the coil in the mast circuit. The

plotted horizontally and the height of the antenna plotted vertically. Curve A was found by trial to have approximately the equation

$$(H_a - 11.8)(C_4 - 84.6) = 88, \tag{a}$$

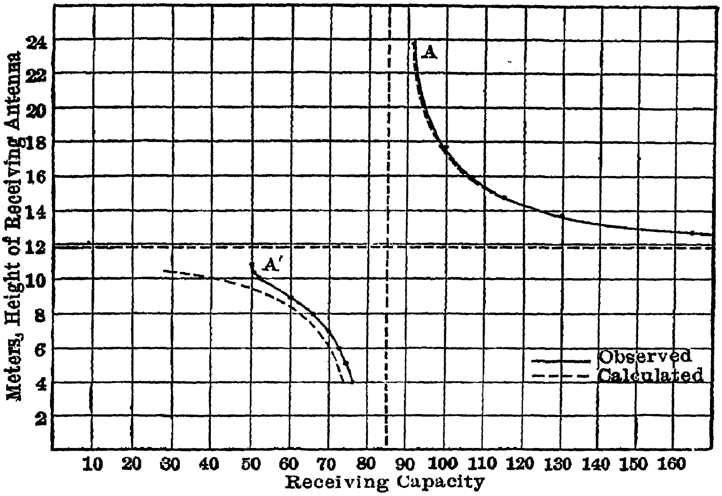

FIG. 199. Relation of resonant receiving capacity to height of receiving antenna.

as is shown by the following comparison of observed values, with values calculated from this equation (Table XIV):

TABLE XIV

RELATION BETWEEN HEIGHT OF RECEIVING ANTENNA AND RESONANT CAPACITY. FOUR WIRES RECEIVING

Curve No., Fig. 196.	Meters Antenna Above Coil, H_a.	Maximum Deflection, cm.	Resonant Capacity Observed, C_4	Resonant Capacity Calculated.
1	23.8	64	92	91.9
2	20.8	47	94	94.4
3	17.8	43	100	99.3
4	15.8	29.5	106	106.6
5	14.8	21	115	113.9
6	13.8	13	130	128.6
7	12.8	7.5	165	172.6

The only large difference between the observed and the calculated value of resonant capacity is in the case of Curve 7, where

The two groups when plotted with resonant receiving capacity against height of antenna form a curve of two branches A, A', Fig. 199. Values calculated from the equation (a) are plotted as the dotted lines in Fig. 199. The heavy curves are the observed values. From a comparison of the observed values with the computed values, we see that our equation, although it led us to look in the right direction for the resonance, is yet an imperfect equation. There are other terms in it beyond those here set down.

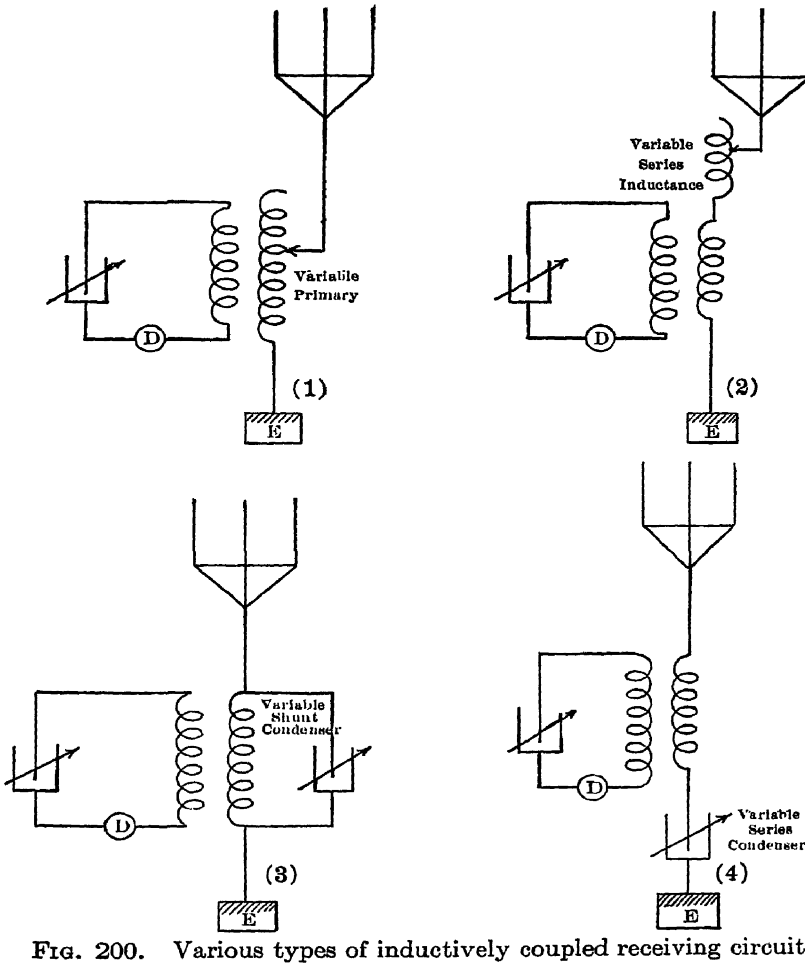

FIG. 200. Various types of inductively coupled receiving circuits.

Applicability of these Experimental Results to Practice. — One may ask, what is the use of this experiment in which the receiving transformer is kept constant and the length of antenna and the

shows that the following is approximately[1] the relation between the several wave lengths in order to produce a maximum current in the condenser circuit:

$$\left(\frac{1}{\lambda_c^2} - \frac{1}{\lambda^2}\right)\left(\frac{1}{\lambda_a^2} - \frac{1}{\lambda^2}\right) = \frac{\tau^2}{\lambda^4}, \tag{1}$$

in which τ is the coefficient of coupling at the receiving station.

By a maximum current in the condenser circuit one or another of the maxima of the twelve different curves of Fig. 198 is meant. Not all of these maxima are equally strong, nor is the resonance for all of the maxima equally sharp. But for nearly any value of λ_a we can get a value of λ_c that will give resonance of a more or less pronounced character.

Let us try a few numerical examples that will make this clear. Let $\tau = .20$; and suppose waves are arriving of wave length $\lambda = 400$ meters. Suppose that our antenna wave length is set at $\lambda_a = 300$ meters. Then we have

$$\tau = .20,$$
$$\lambda = 400,$$
$$\lambda_a = 300,$$

to determine λ_c. With these numerical values equation (1) becomes

$$\left\{\frac{1}{\lambda_c^2} - \frac{1}{(400)^2}\right\}\left\{\frac{1}{(300)^2} - \frac{1}{(400)^2}\right\} = \frac{(0.20)^2}{(400)^4}.$$

Multiplying by $(400)^4$ we get

$$\left(\frac{400^2}{\lambda_c^2} - 1\right)\left(\frac{400^2}{300^2} - 1\right) = .04.$$

Whence $\lambda_c = 390$ meters. This 390 meters is the wave length at which we must set our receiving condenser (in a coupled circuit) in order to receive a 400-meter wave, provided our antenna is set for a 300-meter wave.

Carrying through similar computations for other values of the wave length of the incident waves we obtain the results recorded in Table XV.

[1] In the derivation of this formula the small effect of resistance on the wave length was neglected; also the capacity of the antenna was considered localized instead of distributed. The formula (of which our equation (a) is a special case) is, therefore, inexact, but will serve to illustrate some interesting facts about the tuning of a receiving station.

This curve shows several facts of interest. It shows, for example, that when we have been receiving a wave length slightly shorter than our antenna wave length, and a wave comes in slightly longer than our antenna wave, we must actually decrease our receiving capacity to bring the longer wave into resonance. It shows also that any particular adjustment of our receiving capacity is resonant for two different waves. For example, with our antenna set at wave length 300 meters, and our condenser circuit set for 400 meters, we are really in tune for either a 290-meter wave or a 410-meter wave, not in the best tune, it is true, but sufficiently in tune to be disturbed if the interfering signals are strong.

Advantage of Varying Coefficient of Coupling in Tuning. — There are times when we wish to be in tune for two wave lengths at once, because the station we are receiving usually sends out two waves at once. If we set our receiving condenser at 300 meters, we are in tune for a 270-meter and a 330-meter wave, and these might well be sent out by the same station. They will in fact be sent out by the same station, if it has the same coefficient of coupling as our receiving station, $\tau = .20$, and has its condenser circuit and antenna circuit tuned to 300 meters.

This suggests an important improvement in our tuning mechanism at the receiving station; namely, a device by which we can change the coefficient of coupling at the receiving station and thus make the receiving coefficient of coupling identical with the coefficient of coupling of any particular station we wish to receive. This device[1] is employed in many of the recent receiving sets, and consists of an adjustment by which the primary coil of the receiving transformer may be either moved away from or rotated with respect to the secondary coil. The same result can be attained by cutting out inductance in the primary of the transformer and putting it in series where it will not be in inductive relation with the secondary coil.

Effect of Variation of the Coefficient of Coupling on Sharpness of Resonance and on Received Energy. — Theory shows that diminution of the coefficient of coupling increases the sharpness of resonance. At the same time this diminution of coefficient of coupling brings with it a decrease of energy. I tried some experiments to see what improvement in sharpness of resonance we might

[1] On account of the high resistance of the detectors the proper adjustment of the coefficient of coupling is not one of exact equality with the coefficient of coupling of the sending station, but must be determined by trial.

EFFECT OF RESISTANCE OF DETECTOR ON RESONANCE IN COUPLED WIRELESS TELEGRAPH CIRCUITS

Although the coefficient of coupling of the coupled circuits influences somewhat the sharpness of resonance, a far greater influence in the case of the practical stations is exercised by the resistance of the detectors which are used in the reception of the signals. These detectors, when sufficiently sensitive to respond to weak signals, have a very high resistance. We have seen in Fig. 150 (p. 226) how a high resistance inserted in a simple circuit consisting of a condenser in series with an inductance renders the resonance dull. With the coupled circuits the effects are somewhat more difficult to present, and it is necessary to examine the resonance curves obtained by varying both the antenna wave length and the condenser-circuit wave length in order to ascertain the influence of resistance on the sharpness of resonance.

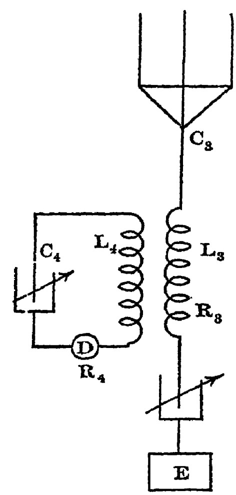

FIG. 204. Diagram of circuit providing for variation of wave length of primary and secondary by variable condensers.

I have submitted the problem to a mathematical examination, and without giving the steps of the reasoning, I take the liberty of presenting some of the results. The form of receiving circuits to which the discussion applies is shown in Fig. 204. The following constants of the circuits were assumed in the computations:

L_3 = Self-inductance of the antenna circuit $= .3 \times 10^{-3}$ henry,

L_4 = Self-inductance of the condenser circuit $= .5 \times 10^{-3}$ henry,

M = Mutual Inductance $= .2 \times 10^{-3}$ henry.

τ^2 = Square of coefficient of coupling $= .267$,

λ = wave length of incoming waves = 472 meters.

The antenna circuit was given various resistances, R_3, and the condenser circuit various resistances, R_4. The resistance R_4 resides chiefly in the detector, and the resistance R_3 includes the apparent resistance due to distributed capacity in the antenna.

The incoming waves were supposed to be a persistent train of undamped waves.

Computations were made for two cases: I, When we fix the antenna adjustments at their best values, and tune with C_4;

Case I (Continued). $R_3 = 10$ Ohms, $R_4 = 10{,}000$ Ohms. — Suppose, now, that the detector should have 10,000 ohms resistance instead of 64,000 ohms. With this reduced resistance the curve marked " $R_4 = 10{,}000$ " is obtained. With this value of R_4, tuning by the condenser C_4 is possible, but the resonance is dull as is indicated by the obtuseness of the curve.

Appropriate adjustment of the antenna in this case is at the line marked "10,000" on the bottom margin; namely, $\lambda_3 = 470$ meters.

Case I (Continued). $R_3 = 10$ Ohms, $R_4 = 1000$ Ohms. — The curve marked " $R_4 = 1000$ " is obtained; and the antenna must be shifted to the line on the bottom margin marked "1000"; that is, the antenna wave length must be set at 460 meters for best resonance. The resonance curve " $R_4 = 1000$ " is much sharper than those obtainable with the higher resistances.

Case I (Continued). $R_3 = 10$ Ohms, $R_4 = 100$ Ohms. — Reference is made to the curve marked " $R_4 = 100$," and to the line at the bottom margin marked " 100." The resonance is sharper than with the higher resistances, and the appropriate adjustment of antenna wave length has shifted to $\lambda_3 = 430$ meters.

Case I (Concluded). $R_3 = 10$ Ohms, $R_4 = 10$ Ohms. — Two resonance positions appear in this case: one at 400 meters (wave length of the condenser circuit), with appropriate adjustment of antenna at 360 meters; and the other at 610 meters (condenser circuit), with antenna adjustment at 810 meters. The resonance here is extremely sharp, especially for the adjustment of condenser C_4 in the neighborhood of 400 meters.

Case II. Let us now suppose a detector circuit of resistance 10,000 ohms, and let us set the condenser C_4 of this detector circuit at its resonant value in the neighborhood of 135 meters (see the diagram for Case I), and then tune with the antenna circuit; for example, by varying the condenser C_3. The results are given in Fig. 206, the different curves corresponding to different values of R_3 in the antenna circuit. From these curves it will be seen that even with a high-resistance detector ($R_4 = 10{,}000$ ohms) the tuning in the antenna circuit is sharp, provided the antenna effective resistance is low (curve marked " $R_3 = 10$ "). With increase of antenna resistance the resonance becomes less sharp.

In practice with a system of coupled circuits like that under discussion and with the high-resistance detectors in use, it is difficult to realize sharper resonance than that shown in the curve

to Fig. 207 that if a receiving station is attuned for a 500-meter wave, it will receive also about 7% as much energy from a 400-meter or a 600-meter wave as it does from the 500-meter wave. From a station emitting a 300-meter or a 700-meter wave the disturbing energy will amount to about 2% of the energy received from the 500-meter wave; while from a sending station emitting a 200-meter or a 800-meter wave the disturbing energy will be below 1%. These statements are on the assumption that all of the stations would give the same received energy if the receiving station were in tune for them.

These computations, although not claiming to be highly accurate, will give a crude idea of about the extent to which interference can be prevented by the use of the coupled circuits consisting of a condenser circuit containing the receiving instrument inductively or directly coupled to an antenna circuit.

There are other methods of coupling receiving circuits to prevent interference which will attain better discrimination between desired and undesired signals, but these almost always greatly reduce the intensity of signals, and cannot be employed for the reception of signals from stations at a great distance from the receiving station.

bolic cylindrical surface and were connected to a spark terminal S_1. Another similar set of strips B_1, B_2, B_3 . . . below the first set were also provided with a spark terminal S_2. The oscillations are produced by a discharge across the spark gap S_1S_2. This arrangement, which, according to the inventor, would send out electric waves in one direction, does not seem to have met with practical success.

Braun's Phase-difference Oscillator. — Another method proposed by Ferdinand Braun[1] makes use of two or more vertical oscillators at certain distances apart provided with means of

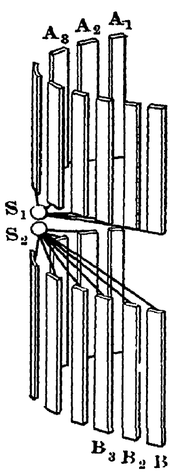

FIG. 208. Braun's parabolic oscillator.

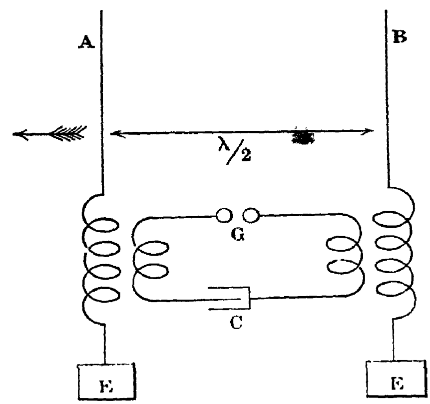

FIG. 209. Braun's phase-difference oscillator for directed wireless telegraphy.

exciting in the oscillators waves suitably differing in phase. For example, if the two antennæ A and B, Fig. 209, are one half wave length apart, and if the oscillations in the two antennæ are opposite in phase, the two sets of waves sent out will add in directions in the plane of the two antennæ and will neutralize each other in a direction at right angles to this plane.

Suitable phase difference in the antennæ may be partially attained by the use of a condenser circuit coupled with the antennæ, as shown in Fig. 209. With this arrangement the problem is, however, complicated by the occurrence of oscillations of double periodicity. This difficulty has been removed in a very

[1] U. S. Patent, No. 776,380, filed July 26, 1904, issued Nov. 29, 1904.

Explanation of Directive Radiation from Marconi's Bent Antenna. — Professor Fleming,[1] Dr. Uller,[2] Dr. Zenneck,[3] and others, have given explanations of the cause of the directive radiation from the Marconi horizontal antenna. All of these writers employ the theory of images as a starting point, by which means the antenna and ground connection of Fig. 210 is replaceable by the equivalent system of Fig. 212.

Fleming's Explanation. — In further explanation, Professor Fleming takes a rectangular circuit of the form shown in Fig. 213, and imagines a current flowing around the rectangle in the direc-

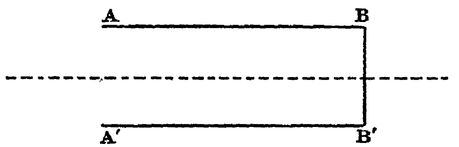

FIG. 212. Marconi directed antenna and its image.

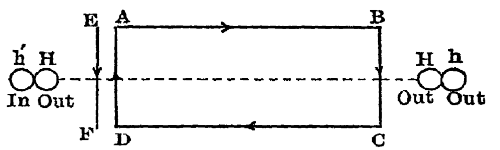

FIG. 213. Diagram used by Professor Fleming in explanation of the directive action of the Marconi bent antenna.

tion of the arrows. This current creates a magnetic field, the direction of which along the surface of the earth is at right angles to the plane of the paper; and at equal distances from the center, the magnetic force represented by H is toward the spectator on both sides. Now, suppose a wire EF equal in length to one side of the rectangle to be placed contiguous to one vertical side, and to carry a current opposite in direction to that in the side of the rectangle (left hand) to which it is in proximity; then the magnetic field of this straight current is h' *from* the spectator on the left-hand and h *toward* the spectator on the right-hand side. Accordingly, the total field $H + h$ on the right is greater than the total field $H - h'$ on the left, because, according to Professor Fleming, the individual fields are added on one side and subtracted on the other. Now, since the two oppositely directed currents in the

[1] J. Fleming: Phil. Mag., Vol. 12, p. 588–604, 1906.
[2] Carl Uller: Phys. Zeitsch., Vol. 8, p. 193, 1907.
[3] J. Zenneck: Phys. Zeitsch., Vol. 9, p. 553, 1908.

Chapter XV, the electric force at the surface of the earth, wherever it is not a good conductor, leans forward, so that we can ascribe to the electric force in a particular case a mean direction,

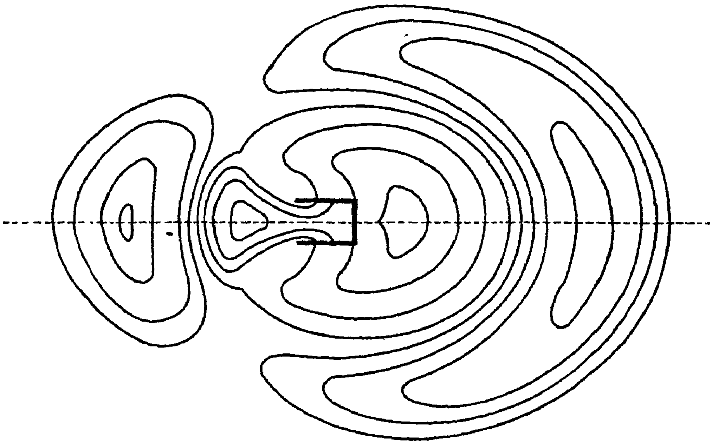

FIG. 214. Dr. Uller's diagram of field of electric force about the bent antenna.

E, Fig. 215. Now the direction of propagation is perpendicular to *E*; i.e., in the direction *S*, whence there is penetration of the energy into the earth's surface and a consequent absorption, so

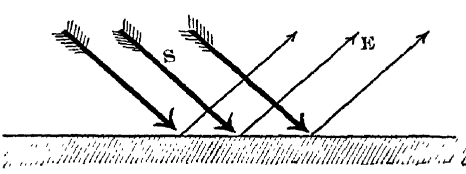

FIG. 215. Diagram used by Dr. Zenneck in explaining directed wireless telegraphy.

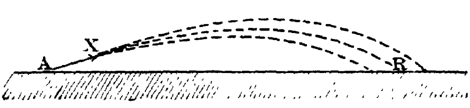

FIG. 216. Zenneck's diagram showing the course of the radiation from *A* to *R*.

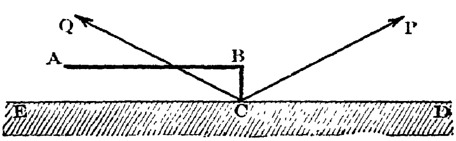

FIG. 217. Diagram applying to Zenneck's explanation.

that the distant receiving station is reached by the energy that started in the direction *AX*, Fig. 216, and not by the energy that started along the surface of the earth. By examination of Fig.

placed within the two coils m and n and is capable of rotation about an axis through o.

Electric waves coming from any particular direction produce oscillation in the two antenna circuits with intensities respectively dependent on the direction from which the waves come. The oscillations thus set up, passing through the coils m and n, compound to form a single magnetic field with a direction perpendicular to that from which the waves come. The strength of the induced current in the movable coil s will depend on its orientation with respect to the resultant magnetic field, and will be a maximum when the coil s is in a position to embrace as many as possible of the lines of magnetic force. This optimum direction is perpendicular to the field, and therefore parallel to the direction from which the waves are coming.

It is therefore possible to determine the direction from which the waves are arriving by merely providing the rotating coil s with a pointer in its own plane. When a maximum strength of signals is received the pointer is directed either toward or away from the signaling station. The final ambiguity as to whether the signaling station is in the direction of the pointer or in the opposite direction would have to be removed by some additional general knowledge of the probable location.

A sending station, devised also by Bellini and Tosi, and capable of directively transmitting signals, consists of a similar aerial system and a similarly rotatable interior coil. The latter is, however, connected with a discharge condenser instead of with the receiving mechanism. The processes involved are, then, the reverse of those entering into the receiving apparatus.

Limitations of Directive Wireless Telegraphy. — The several directive devices above described act directively only in a general way; that is, some more energy is sent in one direction than in other directions, but there is still a considerable diffusion of energy in all directions. The economy effected in the energy of transmission does not seem to be very great, particularly because the closed loops, or nearly closed loops, are not such good radiators or receivers as the straight vertical antenna. However, whenever the bent antenna is installed in land stations the orientation to effect maximum transmission in the most useful direction is generally chosen. Also, it has been proved to be entirely possible with each of the principal systems to determine the direction of the receiving station from the sending station. This achievement does not seem to have

CHAPTER XXVI

WIRELESS TELEPHONY

Sketch of the Method of Wireless Telephony by Electric Waves. The circuits employed in wireless telephony by electric waves resemble very closely those used in wireless telegraphy.

The transmitting apparatus for wireless telephony makes use of a persistent train of electric waves of high frequency sent out from an antenna. Instead of interrupting these electric waves by a key, as in telegraphy, modifications by the voice, corresponding to spoken words, are impressed upon them. These modifications by the voice are applied to the electric waves by means of a carbon transmitter, or similar instrument, placed in the sending circuit or connected with it.

The receiving apparatus is indentical with that employed in wireless telegraphy, and makes use of a receiving antenna coupled with a circuit containing some type of rectifying detector; e.g., an electrolytic detector, a crystal-contact detector, or a vacuum-tube rectifier. About the detector is shunted a sensitive telephone receiver.

The action is as follows: If an unmodified train of electric waves having a frequency higher than the limit of human audibility (35,000 vibrations per second) arrives at the receiving station, the receiving circuit, if properly tuned, will sustain electric oscillations which, passing through the detector, will be rectified and will give a series of rectified impulses to the receiving telephone circuit. These impulses, being all in one direction, will act as a continuous pull on the telephone diaphragm, — a continuous pull for the reason that the diaphragm cannot follow the rapid successive impulses, and because also, on account of the inductance of the telephone circuit, these impulses are modified electrically into a practically continuous current through the receiver.

Having in mind that a continuous train of high-frequency waves produces a continuous pull on the receiving telephone diaphragm, let us now suppose that words are spoken into a carbon transmitter at the sending station in such a manner as to modify the emitted

with it, a wave length suitable for wireless telephony, namely, $3 \times 10^8/75{,}000 = 4000$ meters. With this apparatus, Professor Fessenden reports that he has carried on telephonic communication between Brant Rock, Massachusetts, using an antenna 440 feet high, and New York, using an antenna 200 feet high. The distance between these two stations is about 200 miles. Recently Professor Fessenden also reports successful wireless telephonic communication between Brant Rock, Massachusetts, and Washington, D. C., a distance of about 600 miles.

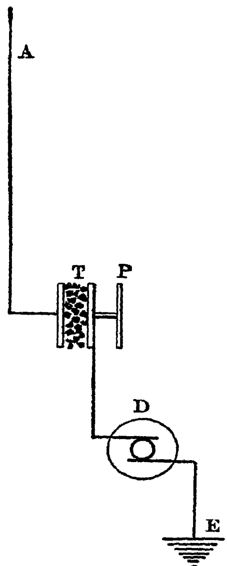

FIG. 219. Professor Fessenden's apparatus for wireless telephony, using high-frequency generator *D* and a microphone transmitter *T*.

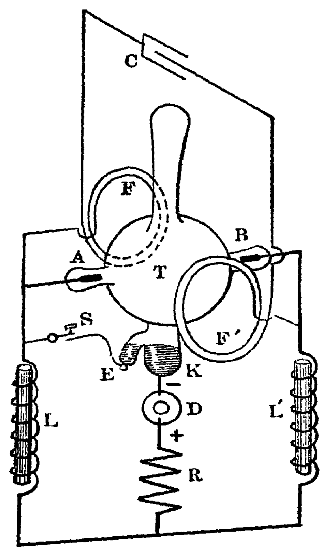

FIG. 220. Diagram of Vreeland's mercury-arc oscillator.

The Mercury-arc Method of Producing Sustained Oscillations. — In 1906 Mr. Frederick Vreeland[1] described a very interesting method of getting practically pure sinusoidal undamped oscillations from a direct-current supply. One form of Mr. Vreeland's apparatus is shown in Fig. 220. *T* is a glass vessel, exhausted to a high vacuum, and containing a mercury cathode *K* and two carbon anodes *A* and *B*. *E* is a small auxiliary electrode used in starting an arc in the chamber. The arc, when established, being fed from the direct-current source *D*, is divided into two branches

[1] Physical Review, Vol. 27, p. 286, 1908.

up to the pitch required for wireless telephony. His apparatus is, however, very ingenious and full of promise.

Method of Applying the Microphone to Modify the Oscillations. — Having described methods of producing sustained or

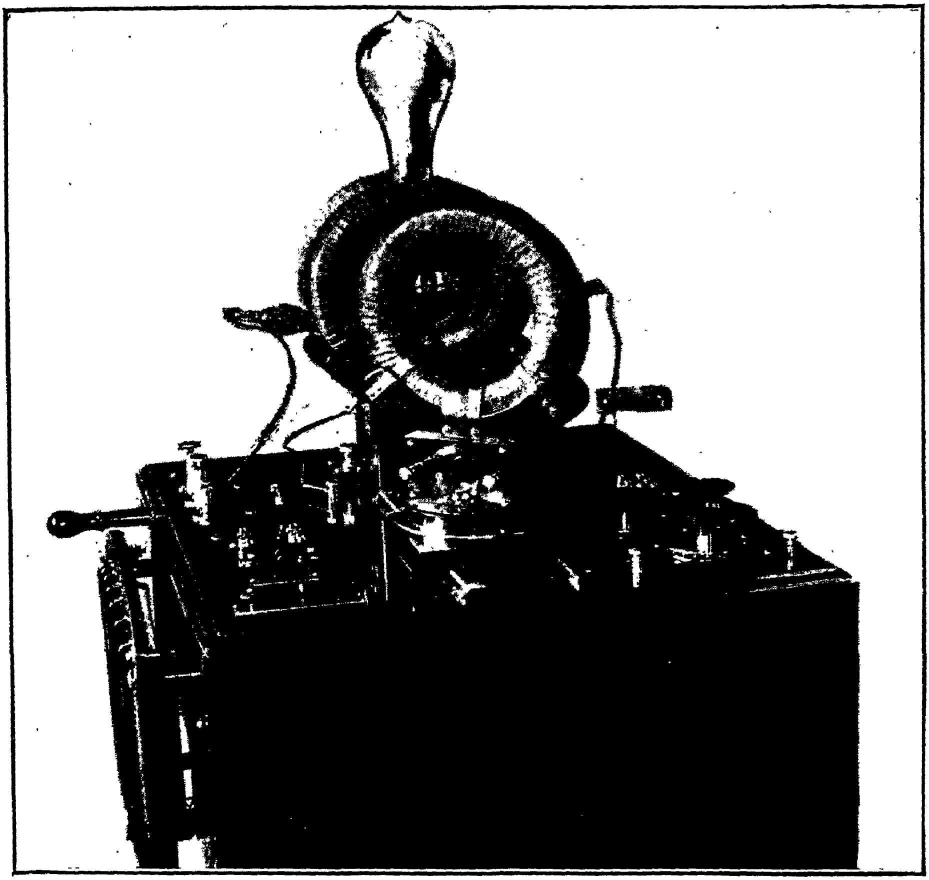

FIG. 221. View of Mr. Vreeland's apparatus.

persistent oscillations I wish next to show briefly diagrams of connections by which the carbon microphone may be applied to modify these oscillations in accordance with the vibrations of the voice. In most of these diagrams I have represented the source of the persistent oscillations as a singing arc, such as has been devised by Simon, Duddell, and Poulsen. It will easily be seen how these

that the microphonic modifications of current have to traverse the generator circuit, and hence meet with high impedance.

Figure 224 shows the microphone connected in series with the antenna circuit, between the secondary of the oscillation transformer *PS* and the ground connection.

Figure 225 shows a method proposed by Mr. Vreeland and others in which the microphone circuit is inductively connected with the secondary *S* of the oscillation transformer.

Other methods of connecting the microphonic transmitter to the oscillating circuit are also employed.

Practical Results in Wireless Telephony.—I have briefly pointed out in the preceding paragraphs the general processes employed in wireless telephony. The small amount of space here devoted to the subject is not to be taken as evidence that wireless telephony is a simple or unimportant branch of the science of electric-wave transmission of intelligence.

To be able to modulate a train of electric waves by waves of sound existent in the air between the mouth of the speaker and a transmitting diaphragm, and to be able to receive these modulated electric waves at a distance and reconvert them into sound waves, is a very remarkable achievement of scientific ingenuity, even when the sending and receiving stations are close together. Wireless telephony has, however, gone far beyond this stage; and Fessenden in America, Poulsen in Denmark, Majorano in Italy, and Messrs. Colin, Jeance and Mercier in France, have severally reported successful wireless telephonic transmission of speech to distances ranging from 40 to 600 miles. Even if these experiments have been lacking in some details of perfection, we cannot doubt that practical wireless telephony, especially between ships at sea at a considerable distance apart, is a possibility of the present time or of the immediate future.

travels out along the surface of the earth induces currents in the earth and is rapidly absorbed. The remainder of the energy radiated from this horizontal portion travels prevalently upward and, save for contributing to the directiveness of transmission as has been pointed out in Chapter XXV, does not have much effect at the receiving station unless it is desired to transmit to a balloon, when this upward-traveling component is most useful.

The horizontal portion of the flat-topped antenna is, therefore, chiefly serviceable as a capacity at the top of the vertical part, which latter is the chief radiating member. As to the amount of the capacity it is interesting to note that a single wire 100 feet long and $\frac{1}{8}$ inch in diameter when alone in space has as much capacity as an isolated flat metallic disc 16 feet in diameter. (See formulas for calculation in Appendix II.) From this it will be seen that the horizontal top to the antenna is a far more economical elevated capacity than any kind of a metallic sheet such as was employed in Marconi's early experiments.

Comparison of Flat-topped with Straight Antenna. — In order to illustrate some of the principles involved, let us next compare the radiation from a single vertical wire 100 feet long and say $\frac{1}{8}$ inch in diameter with that from a flat-topped antenna consisting of a vertical wire 100 feet long having at the top a horizontal extension of the same length. For the purpose of this comparison we shall employ the experimental curve of current distribution found in Chapter XIV (Fig. 82). In the first place the flat-topped antenna, because of its greater length of wire, has approximately twice as much capacity as the simple vertical antenna. This means that if we charge the two antennæ to the same potential, about twice as much electricity will flow during one oscillation of the flat-topped antenna as during one oscillation of the simple vertical antenna; but the time of the oscillation in the former case will be about twice as long; therefore the maximum current flowing to the ground will be about the same in the two cases. Let us now plot the approximate current-distribution curves for the two cases, assuming the same current at the base; and in doing this we shall make the further assumption that the distribution in the bent antenna is approximately the same as it would be for a straight antenna of the same length. The curves obtained are given in Fig. 227. In these curves the value of the current at any point of the length of the antenna is plotted as a distance between

base is not multiplied in the ratio that the number of wires is multiplied.

For an economical installation from four to six wires may well be employed in the antenna, and by the use of light bamboo spreaders they can easily be supported three feet or more apart.

Marconi Antenna at Clifden. — An example of the use of the flat-topped antenna on a large scale is afforded by the Marconi high-power station at Clifden, Ireland. The horizontal part of the antenna of this station consists of 200 wires 1000 feet long supported 180 feet above the earth The wave length is about 4000 meters.

The Umbrella Antenna. — When only one supporting pole is available, either the straight type or the umbrella type of antenna

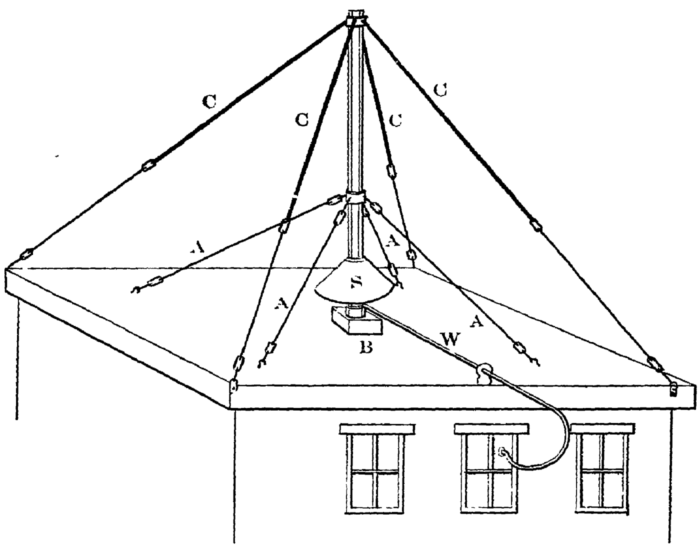

FIG. 228. Umbrella type of antenna.

is usually employed. The umbrella type meets with frequent use in small amateur stations and in the portable stations employed by armies. In this type the aerial system consists of a vertical portion terminating above in a system of wires inclining downward. These inclining wires are usually the guy wires, while the vertical part may be either a wire leading to the top of the pole, or the pole may itself be of metal and serve as the vertical conductor. A diagram of an umbrella type of antenna with a metallic pole serving as the vertical conductor is shown in Fig. 228. The

ity of a wire the same length and $\frac{3}{8}$ of an inch (1 cm.) in diameter. Therefore, so far as concerns capacity, a few small wires five or six feet apart would be the equivalent of this large steel tube.

The Ground. — The theory of the action of the ground has been discussed in Chapter XIV. In practice, for a small station a satisfactory ground can be obtained by a connection to the pipes of a water supply. Where this is lacking, a good arrangement is to bury a netting or network of wires at a short depth below the surface of the earth. This may be supplemented by metallic pipes driven to considerable depths into the earth, and also by wire netting spread out on the surface of the earth. When the station is located near the sea or other body of water, the wire netting or wires provided with terminal plates may be led into the body of water. On board ship, the grounding is usually effected by a heavy wire attached to the metallic hull of the ship. In the high-power land stations, netting and wires are made to ramify the surface of the earth for many acres.

We have seen in Chapter XIV that a properly resonant artificial conductor supported without contact with the earth serves as a very good ground. The difficulty about the artificial ground is the fact that the artificial ground should be tuned along with the aerial system in order to get resonance with different wave lengths.

Sending Condensers for a Coupled Transmitting Station. — The details of construction of the simple Marconi apparatus of 1896 need not be given. When a sending station of the inductively coupled or direct coupled type is to be employed, the sending condensers must be electrically strong in order to permit the storage of the large quantities of electricity used in producing the waves. Among the types of condenser employed for this purpose the bank of Leyden jars or of flat glass plates provided with metallic coatings are most familiar. The use of tinfoil, for the coating of Leyden jars or flat-plate condensers for use in wireless telegraphy, has been largely discontinued. In the case of the flat-plate condensers copper or brass sheets between the plates in the place of the tinfoil that was formerly much used gives a much smaller loss of energy, and consequently much smaller heating of the condenser. Ordinary window glass, when selected free from flaws, is electrically stronger than plate glass for making glass-plate condensers. When high power is to be used, the flat-plate condensers should be submerged in castor oil to prevent brush discharge.

In the case of the Leyden jars, when used in stations of large

voltage at which the discharge occurs. As a specific example, let us suppose that the power is to be supplied by an alternating current source of n cycles per second. By means of a transformer with its primary connected to the source of power and its secondary attached to the condenser, we may step up the potential to the value required to produce the required spark. Let us suppose the transformer to supply P kilowatts of power to the condenser, and let us choose the condenser and the spark gap to be such that the condenser charges to a sparking potential only once during each half-cycle; that is, $2n$ times per second.

Now to charge a condenser *once* to a potential of V volts requires an amount of energy,

$$W = \tfrac{1}{2} QV \text{ joules,} \tag{1}$$

where Q is the number of coulombs of electricity required and $\frac{1}{2}V$ is the average potential during the charge. (See Appendix I.)

And, from the definition of capacity,

$$Q = CV, \tag{2}$$

where C is the capacity of the condenser in farads.

Substituting the value of Q from equation (2) in equation (1), we have

$$W = \tfrac{1}{2} CV^2 \text{ joules,} \tag{3}$$

V being the potential in volts to which the condenser is charged.

In our supposed case the condenser is charged $2n$ times per second; therefore the energy expended per second, which is the power supplied, is

$$W = 2n \times \tfrac{1}{2} CV^2 = nCV^2 \text{ joules per second.} \tag{4}$$

But 1 joule per second is 1 watt, and 1000 watts make a kilowatt; therefore if P is the power in kilowatts,

$$P = \frac{nCV^2}{1000} \text{ kilowatts.} \tag{5}$$

In interpreting this formula, it must be remembered that V is the potential to which the condenser is charged at the time that the spark begins.

The formula (5) is very useful in practical computations. By a simple transposition of terms, equation (5) may be put in the form

$$C = \frac{1000 \times \text{Power in Kilowatts}}{nV^2}\,. \tag{6}$$

will draw a very small amount of power, and allow the spark to extinguish promptly after the discharge of the condenser.

A mathematical examination of this problem shows that this result can be obtained with a proper adjustable resistance placed in the primary circuit of the transformer, if a common closed-core transformer is used. The same result can be more economically obtained by the use of an adjustable inductance in series with the

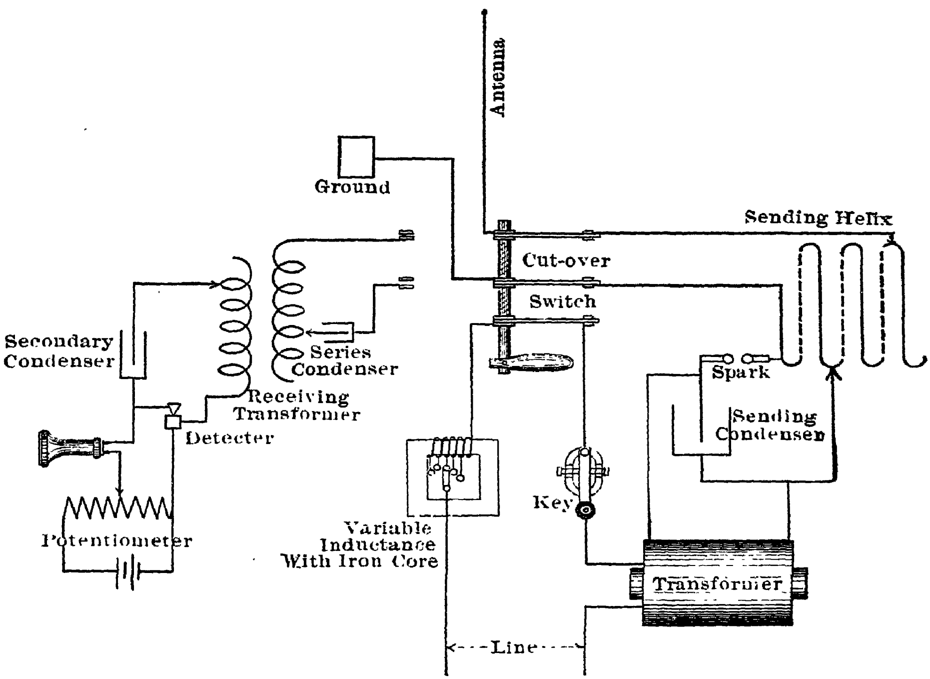

FIG. 230. Diagram of transmitting and receiving installation.

primary. It can also be attained by an adjustable inductance in series with the secondary of the closed-core transformer.

With an open-core type of transformer and an adjustable inductance in the primary circuit considerably greater flexibility in attaining resonance with condensers of different capacities is possible, and many engineers prefer the open-core transformer.

Sending Helix. — The construction of the sending helices of the direct-coupled and the inductively coupled type is shown in the photographs of Figs. 166 and 168 respectively.

Sending Key. — With power not exceeding 5 kilowatts at a

ground are joined to the primary of the inductively connected receiving transformer, and the line circuit is opened so as to avoid a possible accidental discharge of the high-potential circuit while receiving.

A photograph of a station with approximately the arrangement of circuits here indicated is shown in Fig. 231.

I will next describe some of the parts of the receiving apparatus, and shall employ in the description the designations used in Fig. 230.

Receiving Condensers. — The series condenser, which is employed in the antenna circuit between the primary of the receiving transformer and the ground, should be an air condenser of the semicircular plate type, like that shown in the photograph of Fig. 81. The introduction of this condenser has the effect of shortening the wave length of the antenna, so as to adapt an antenna of long wave length to receive short waves. Tuning by means of this condenser gives a better discrimination of signals according to their wave lengths than can be obtained by the use of adjustments in the detector circuit; nevertheless this series condenser can often be dispensed with.

The secondary receiving condenser, in circuit with the detector, cannot be dispensed with. This condenser may also be of the semicircular air type, but its capacity should usually be larger than can be attained with a single condenser of this type. If the secondary of the receiving transformer is adjustable as to inductance, the secondary condenser does not require to be capable of fine adjustment, and a condenser with mica plates as dielectric, and provided with step-by-step adjustment, may be used. In fact, with adjustable inductances in the transformer, the value of the secondary condenser may well be entirely fixed.

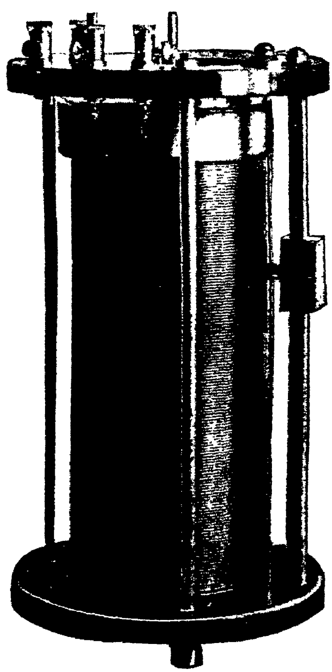

Fig. 232. A receiving transformer.

Receiving Transformer. — A photograph of one type of receiving transformer is given in Fig. 232. The secondary coil of this transformer is shown near the top of the apparatus. The primary

voltage for the local circuit is taken from this resistance by two leads, one to the end of the resistance and the other to the sliding contact. The exterior of a potentiometer in which the resistance

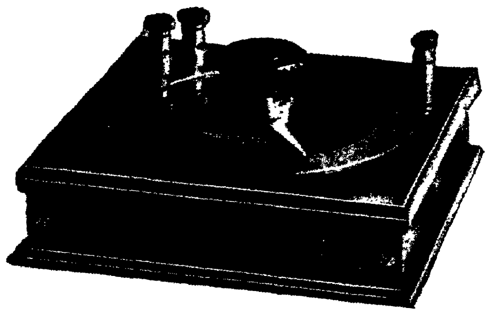

FIG. 233. View of a potentiometer.

is wound on a circular collar and the sliding contact carried by a rotating arm is shown in Fig. 233.

Two electrolytic detectors, mounted on a common base with this potentiometer, are shown in Fig. 234.

With some of the crystal-contact detectors a small voltage in

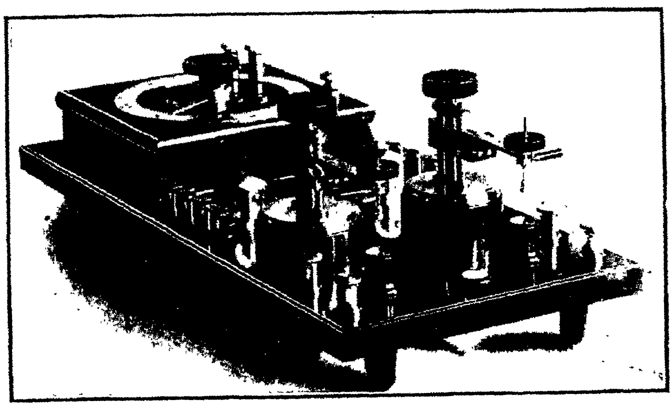

FIG. 234. Two electrolytic detectors with potentiometer.

the local circuit may be an advantage. The potentiometer in this case need, however, employ only one dry cell or one Leclanché cell.

Reliance on Principles Rather than on Details. — The details of construction here given appertain primarily to what is at the present time the most usual type of wireless telegraph station. Progress in this respect is, however, very rapid, and it is not at all